CHAPTER 5

Shadow-Mask Tube

5.1 Principles of Operation

The shadow-mask color picture tube, already touched upon in Section 3.1.1, is discussed in greater detail in this chapter. Figure 5.1 illustrates a typical 25V, 90° tube having a diagonal of 25 in. (25V) and 90° deflection (total sweep across the diagonal).* This tube employs a gun arrangement that generates three independent electron beams. These beams are closely spaced within a common neck, use a common magnetic deflection yoke for scan, and strike a shadow mask having a multiplicity of apertures. The typical shadow mask contains approximately 350,000 apertures in a hexagonal array with center-to-center spacing of about 0.6 mm. Corresponding to each aperture is a triad of red, green, and blue emitting phosphor dots, 0.35 mm in diameter, which are approximately tangent to each other. The

* As a result of a Federal Trade Commission ruling in 1966 on the advertising of TV receivers, the Electronic Industry Association adopted a revised system of nomenclature for commercial color tubes in the United States. A first number followed by "V" indicates the viewable screen diagonal rounded to the nearest inch. Previous to 1966 the first number, without the letter V, referred to the bulb diagonal instead of the screen diagonal. The second and third letters, upon application by a tube maker to the Electronic Industry Association for a tube-type number, are assigned to reflect characteristics such as deflection angle, screen type, mounting hardware. The suffix P22 refers to a three-color phosphor screen. An example of a color-tube-type designation, for a color tube having a diagonal screen dimension of approximately 25 in., is 25VABP22.

In Europe, a similar tube could be designated as A67–120X. In this system, the letter A indicates a picture tube, 67 refers to the bulb diagonal to the nearest centimeter, and the X indicates a color tube. The 120 arbitrarily reflects characteristics such as the deflection angle, screen type, and mounting hardware.

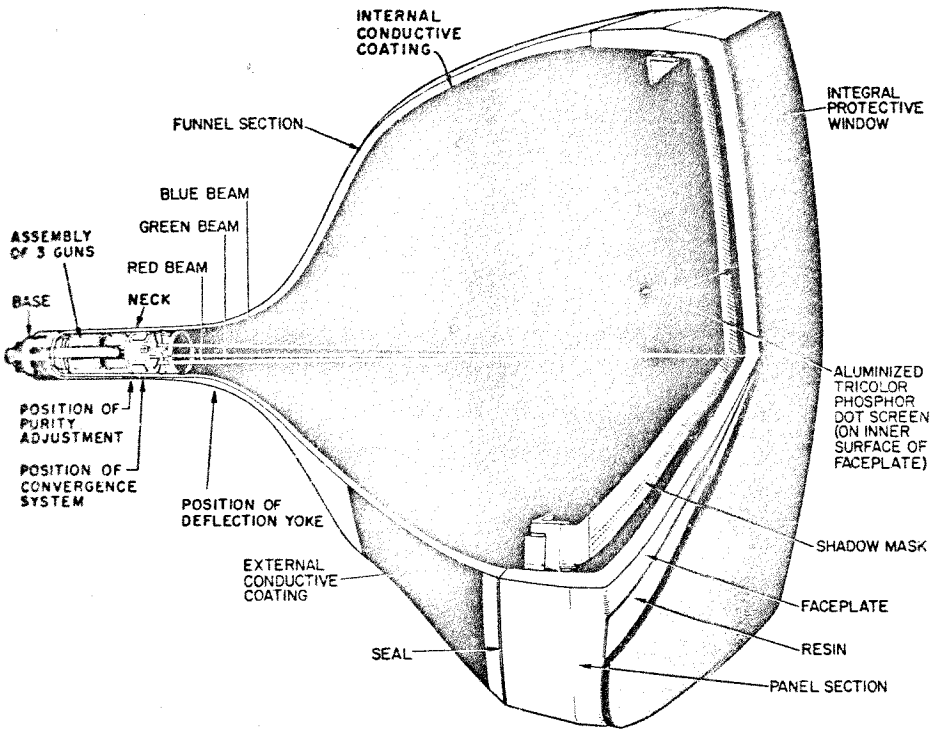

Fig. 5.1. Typical 25V, 90° shadow-mask color tube.

electron guns in a typical tube are arranged in a triangular configuration within a 36-mm outside diameter neck. The three close-spaced electron beams, when undeflected, are aimed at the center of the screen at an angle of 1° from the center line of the tube system. As a result of the spacing of the electron guns from each other, and the 13- or 14-mm separation of the shadow mask and faceplate, the beam from the red gun can strike only the red phosphor elements and is shadowed from the phosphor elements of the other two colors by the aperture mask. A similar situation exists for beams from the green and blue guns. Pure primary-color fields can be obtained by this arrangement and, of course, any combination of primary colors.

In addition to deflection by the common magnetic yoke to produce a scanned raster, a small change in angle of each individual beam is accomplished when needed to obtain convergence of the beams at the screen by activation of internal pole pieces at the anode end of the electron gun (see Section 5.3.6). These internal pole pieces are excited by currents through magnetic components around the neck of the tube. The currents in the

components have wave shapes that enable the three beams, when scanned, to maintain coincidence at all positions on the screen. The incremental deflection induced by these currents, called dynamic convergence, is of the order of 1° for each of the beams.

5.2 Early Shadow-Mask Tubes

5.2.1 Phosphor Screens

The pressures to start color broadcasting in the late 1940's greatly accentuated work on a direct-view color tube. Although several possible approaches existed (*1*), the shadow-mask tube was singled out for concentrated effort. However, a very practical consideration presented itself—how could such a structure be built with the phosphor elements correctly positioned, especially with tubes made in mass production?

At that time the state of the art of depositing phosphor screens for black-and-white tubes involved settling the phosphor powder on the faceplate from a water suspension. Screens consisting of phosphor lines for experimentation with color had been made by covering the surface with a grill of wires or ribbons before settling and then lifting the grill. No method was available for producing such a screen when the mask was located at a distance from the surface as would be required in the shadow-mask color tube.

A solution to the phosphor-element location problem was found in the "lighthouse" principle (*41*). This principle takes advantage of the fact that in field-free space electrons travel in straight paths as does light. Thus, proper location of phosphor elements can be found as the terminal points of light paths at the screen plane when light rays are properly substituted for electron paths. That is, light emitted from a source placed at the center of deflection of one of the electron beams will pass through the mask apertures and strike the screen plane where corresponding phosphor elements should be placed.

In first attempts to employ this principle, a flat metal shadow mask and flat screen were used. The mask was produced by an etching process (*42*) and had a fine enough array to avoid structure visibility problems in the picture. The positions of the phosphor elements were then recorded through this mask on a photographic plate placed at the screen plane and this was used to make a thin metal settling mask by etching apertures in the metal where the phosphor should be placed (*41*). The settling mask was positioned three times against the faceplace surface to settle a nested array of red, green, and blue phosphor elements. However, it soon proved more practical to make a "silk screen" from the photographic plate and to print the phosphor elements instead of settling them (*43*).

In these early experimental tubes, no attempt had yet been made to produce interchangeable flat masks and phosphor screens, so a photographic plate was exposed for each tube and a silk screen made and used to print the phosphor screen. Good tubes could be produced this way, but having to expose a photographic plate and make a silk screen for each tube was a very expensive process to contemplate for mass production of color tubes.

To avoid the need for a photographic plate and silk screen for each tube, effort was directed toward achieving interchangeable flat shadow masks and phosphor screens (*44*). Some progress was made, but there were other practical difficulties. For example, the flat mask, although mounted under tension on a frame, was subject to "oil-canning" when heated by electron bombardment, causing loss of color purity. Also, the internal flat glass phosphor plate could not be safely heated and cooled as quickly as desired for rapid tube processing.

These and other consequences of using flat structures led to placing the screen on the inside surface of the curved faceplate for use in conjunction with a curved mask (*6*). Interchangeable mask and screen structures now became much more difficult to achieve but, on the other hand, the need for interchangeable structures became less acute because of the adoption of a photodeposition process for printing the phosphor (*7*). In this new system, the lighthouse principle is still employed to locate the correct phosphor position; but the need for photographic plates and silk screens is avoided even though noninterchangeable masks are used. The procedure consisted of assigning a given mask to a given glass faceplate panel to make a unique assembly. The screen is then made by first applying one of the color phosphors, mixed with a photosensitive binder, to the screen substrate surface and exposing the mixture through the mask with a UV light source placed at the appropriate deflection center. The binder hardens upon exposure to UV light and retains the phosphor while the unexposed binder and phosphor can be washed away. The process is repeatable and, by deposition of the other two colors, three interlaced arrays of phosphor elements are obtained that are precisely placed. Similar procedures are still used in the production of shadow-mask color tubes.

5.2.2 Bulbs

Early experimental bulbs were round in shape for maximum strength and ease of construction. They were spun out of 430-alloy metal in two parts—a cone section permitting a 45° deflection angle and a topcap or panel section (*45*). Both contained flanges for welding the two parts together. The panel also contained a flange at its other end to which a spherical faceplate glass was hot sealed prior to joining the funnel and topcap. Also prior to this joining, a flat mask-phosphor screen assembly was fabricated as a separate

entity and mounted on brackets at the large end of the metal cone. In a later type, the funnel and topcap were made of glass with the metal flanges hot sealed to the glass (*44*). The flanges were welded for final closure as before, after insertion of the flat mask-phosphor screen assembly. In both the metal and glass-flanged bulbs, the internal mask-screen assembly required very slow warm-up and cooling in processing to prevent breakage of the phosphor screen plate.

As mentioned in Section 5.2.1, the next major innovation was the placing of phosphor directly on the inside curved surface of the panel and the use of a mask with corresponding curvature as the only internally supported structure (*6*). Next a 21-in. round, two-piece metal envelope with 70° deflection (*13*) was developed, also with phosphor on the faceplate. Finally, a two-piece, all-glass bulb was developed which was sealed with glass frit (*15*). Then, even as now (1973), the parts comprised a funnel section and a faceplate panel section with the internal conductive coatings and the phosphor screen applied while the tube is open.

The frit for closing the two-piece color bulb is a low-temperature "solder glass" which works as follows. The solder glass in powder form in an organic binder is applied to the seal edge. The funnel and panel are aligned in a jig and held in contact by gravity. As the temperature is raised the binder burns out and the solder glass becomes vitreous. The fluid glass wets the seal surfaces and fills the gap between them. The temperature is further raised to about 445°C and held for one hour. During this time the solder glass irreversibly devitrifies to a ceramic-like material to make a strong, gas-tight seal.

The two-piece feature of a color bulb is not an additional cost factor because the funnel and panel of even a black-and-white picture tube are made separately. A subsequent hot seal by the bulb maker fuses the two together by melting the glass. In the shadow-mask tube, however, such hot sealing is not permissible because of heat damage to the shadow mask and phosphor screen, which must be in place before sealing.

Two-piece rectangular bulbs with rounded corners and slightly rounded sides were successfully designed (*16*) which enabled more of the transmitted picture to be fully displayed than with round bulbs. In successive designs the corners became sharper and the sides straighter until the picture is now severely rectangular. The tube length decreased as the deflection angle was increased from an initial 45° to 70° and then to 90°. By 1973, 110° deflection was very common.

5.2.3 Electron Gun

Early experimental shadow-mask color tubes were of two types which differed primarily in the way the three electron beams were handled. In

one type a cluster of three guns in the neck of the tube was used. This is the arrangement subsequently developed commercially for the shadow-mask tube (*4*). In the second type, a single gun producing a single beam was employed. Here external magnetic components were used to sequentially position the beam in the neck of the tube so as to simulate the beams in the triple-gun system (*46*). The arrangement performed satisfactorily except insofar as the brightness was severely limited by having current available from only one gun instead of three.

The three closely spaced beams must be coincident or converged at the screen and remain so as the beams are deflected over the screen. Misalignment of the gun structures makes it necessary to provide adjustment for obtaining accurate coincidence of the spots in the center (static convergence) and it is also necessary to provide means to maintain this coincidence during scan (dynamic convergence).

In an early three-gun tube with the guns parallel to one another, an electrostatic lens common to all three beams was used at the anode end of the gun cluster to perform both static and dynamic convergence. Small external permanent magnets were used for fine adjustments of coincidence at the center. An improved system eliminated the electrostatic convergence lens by employing magnetic means for bending the beams to obtain coincidence. In this system magnetic pole pieces in a convergence cage on the gun are actuated by external magnets to give individually controlled radial motions to the beams synchronized with scan. In addition, the blue gun is provided with lateral motion of its beam to give the degree of freedom of motion necessary to insure convergence. The amount and type of motion needed is dependent on deflection-yoke design. The yoke design is also concerned with obtaining maximum screen tolerance as well as achieving acceptable pincushion distortion. However, for larger scan angles, circuit pincushion correction became necessary and emphasis was placed primarily on designing yokes for improved convergence and screen tolerance characteristics.

Each shadow mask color gun must be capable of very high current, relative to a black-and-white tube gun, to produce adequate brightness because much of the beam current is absorbed by the mask and produces no light. High gun currents are needed to help overcome this loss, which requires careful gun design to obtain satisfactory resolution. The situation has been aggravated by a reduction in tube neck diameter from the early 50.8-mm neck size down to 29 mm to avoid increasing deflection power in successive designs as the deflection angle has increased. The advent of in-line gun tubes has further restricted the diameter of the gun lenses that can be used because of the less compact gun structure that must fit into the small neck.

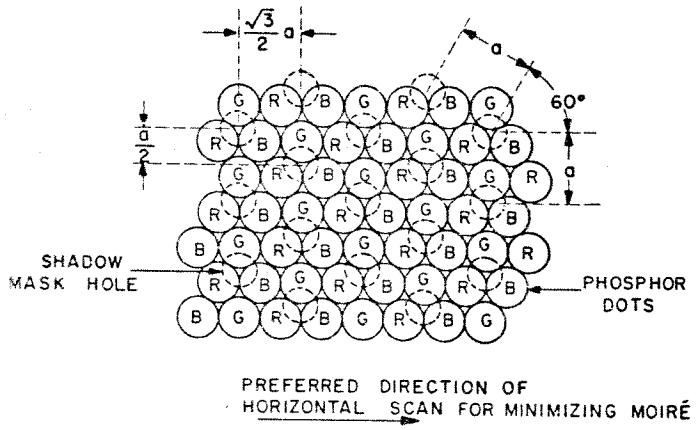

Fig. 5.2. Mask-aperture and phosphor-dot arrays in shadow-mask tube. The dotted circles represent the mask apertures (with diameter B).

5.3 Shadow-Mask Tube Technological Developments

5.3.1 Screen and Mask Geometry

Figure 5.2 shows the basic geometric plan view of a hexagonal array of round apertures in a flat shadow mask, together with the phosphor-dot screen. The apertures have a diameter B and are equally spaced a distance a apart. Figure 5.3 represents a cross section through a line of apertures in a flat mask spaced a distance q from a flat screen. A point source of radiation, offset by an amount s from the color tube axis, is placed a distance p from the mask and L from the screen.

Radiation emitted from the source forms a dot pattern on the screen plate with an element spacing D and a magnification of the mask aperture $\lambda = L/p$. Two other sources, located 120° about the tube axis and also at a distance s from the axis, will form similar patterns that will nest perfectly with the first pattern, provided appropriate dimensions are chosen.

In practice the source has a finite size, m, as indicated in Fig. 5.4. The radiation is UV light when printing the phosphor screen and electrons in the finished tube. If the projected pattern is to form tangent elements of diameter R for maximum screen utilization, then it is easy to show that the following relations hold:

$$q = aL/3s, \qquad R = \sqrt{3}as/(3s - a), \qquad B = (a/3)(\sqrt{3} - m/s) \quad (5.1)$$

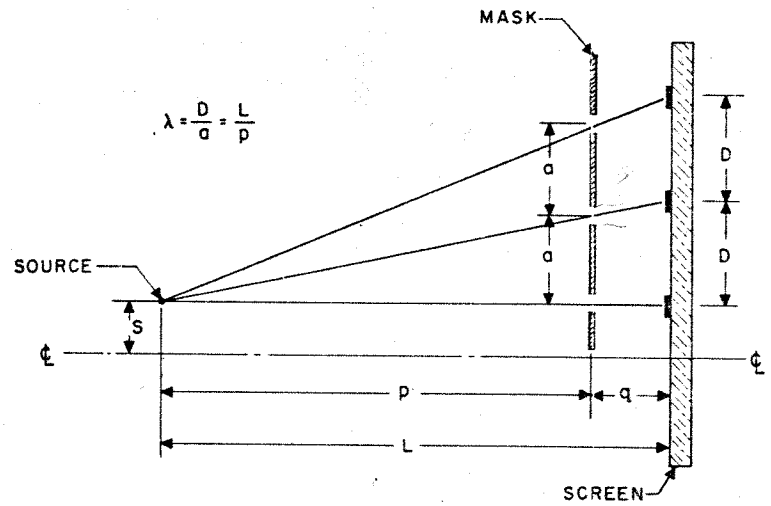

Fig. 5.3. Planar mask-screen geometry.

and the mask transmission is

$$T = (\pi/2\sqrt{3})\,(B/a)^2 \tag{5.2}$$

The geometry of the color tube is somewhat more complicated because the faceplate is spherically curved or may even have a compound curvature in the larger sizes. The mask is also curved to obtain the best possible nest-

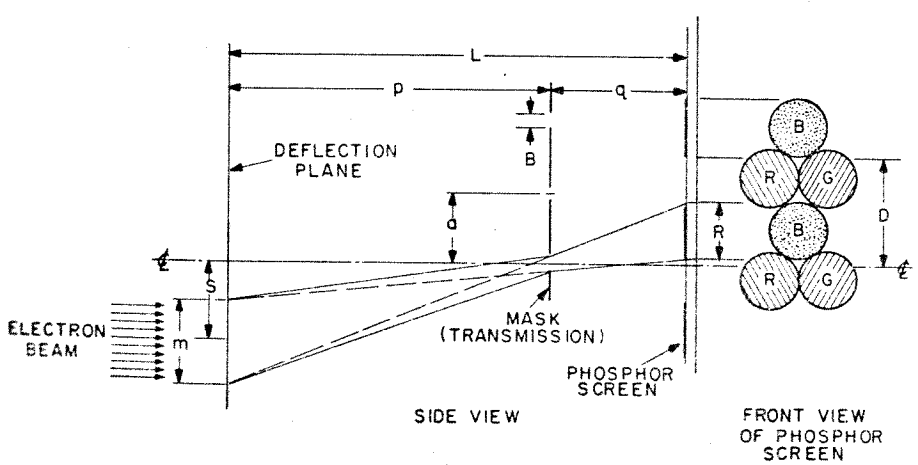

Fig. 5.4. Determination of phosphor-dot size and phosphor-dot nesting.

ing of the phosphor dot patterns on the screen. However, curving of the mask and screen introduces geometric distortions in the beam-landing triads or obliquity errors that do not exist with flat structures. There are other nongeometric errors in the landing patterns that are caused by deflection and convergence of the beams as well as by ambient magnetic fields. These factors will be discussed in Section 5.3.2. However, the effect of geometric relationships between the scanning pattern and the aperture pattern of the mask on the reproduced picture will be considered at this point.

Moiré Considerations

An important consideration in the selection of spacing of apertures in the shadow mask is the influence this spacing has on the interaction of the apertures with the pattern generated by the raster scan lines to produce moiré. If the distance between horizontal rows of apertures in the shadow mask and the spacing between the horizontal scan lines happens to coincide, or is an exact multiple, there may be little effect, but any minor deviation from this coincidence of spacing can easily cause a modulation in the intensity of the beam passing through the mask. Thus, a change in raster height or nonlinear vertical scan may produce a moiré pattern. In any event, it is necessary to carefully select the spacing of the mask apertures so that moiré is held to a minimum.

Consideration must be given to a number of practical factors, first of which is the number of scan lines that will be used for the picture tube under consideration. In the United States 525 scan lines is standard. In much of Europe 625 is the accepted standard, but in some countries 819 scan lines are the standard. In any of these cases the active lines, or the total lines minus the number of lines used for blanking, must be considered in the calculations. A second factor is the amount of overscan that will be used in the particular receiver (causing top and bottom raster lines to be deflected off the screen) since this will obviously affect the spacing of the visible scan lines. A third is the variation that can be expected in the vertical height due to normal variations in line voltages and other factors affecting the circuitry of the vertical deflection system. Pincushion distortion will also affect the spacing of the scan lines to some degree.

Table I gives a set of scan-line spacings and corresponding mask-aperture spacings to give minimum moiré for several sizes of typical picture tubes when used with 525 and 625 scanning-line systems. The mathematical basis for choosing aperture-mask spacings will be given below. In addition, a general criterion is to use an aperture spacing in the mask small enough to

TABLE I

MASK-APERTURE SPACINGS FOR MOIRÉ MINIMA IN SEVERAL COMMERCIAL PICTURE TUBES

U.S. commercial type designation	Raster[a] height (mm)	Screen height (mm)	Aperture spacing, a (mm)	Scan-line spacing, h (mm)	Approx. ratio h/a
		525 Scan-Line System[b]			
25V	423.4	395.8	0.627	0.877	11/8
21V	360.4	336.7	0.650	0.746	9/8
19V	324.5	303.3	0.587	0.672	9/8
		625 Scan-Line System[b]			
25V	411.6	395.8	0.627	0.716	9/8
21V	350.2	336.7	0.676	0.609	7/8
19V	315.4	303.3	0.617	0.549	7/8

[a] Calculated on the basis of 7% overscan for the 525 scan-line system and 4% overscan for the 625 line system.

[b] The 525 scan-line system, with retrace blanking, has 483 active lines; the 625 system has 575 active lines.

minimize visibility of the screen structure, but large enough to avoid excessive practical problems in producing the apertures in the shadow mask and printing the phosphor elements with controlled size.

Mathematical Considerations of Screen Moiré

We will assume that the picture is viewed from a sufficient distance that the dot-triad separation lies well beyond the limit of resolution and that the same applies for the center-to-center spacing of the scanning lines, h. As already mentioned, the interaction of the scanning line pattern with the mask-aperture pattern can give rise to intensity fluctuations, or moiré, in the image field, with a period large enough to be readily visible (*47*, *48*). The variation in intensity of the scanning lines transmitted through the shadow mask, which is responsible for the observed moiré, is minimized when the direction of scan is perpendicular to a set of rows of adjoining apertures (Fig. 5.2). The mask transmission for a scanning line then becomes a maximum when the scanning line is centered on a row of apertures and becomes a minimum when it lies halfway between two aperture rows, a distance $a/4$ away. If the scanning-line separation (in the mask plane)

tain simply

$$\delta x = \frac{(p_0 + q_0) q_0 \sec^3 \theta (1 - \sin^2 \theta \sin^2 \phi)}{2R_0} \tag{5.37}$$

with $R_0 = 33.7\{[V(\text{volt})]^{1/2}/B(\text{gauss})\}$ mm. For example, for a tube with $p_0 + q_0 = 400$ mm, $q_0 = 13.6$ mm, $B = 0.54$ G, $V = 25{,}000$ V, $R_0 = 9867$ mm, we obtain $\delta x = 0.28$ mm for $\theta = 0$. Observed residual displacements in a typical tube using shielding are found to be about 0.05 mm, i.e., less by a factor of the order of 5, indicating the effectiveness of the magnetic shielding. Furthermore, the displacements are not found to increase as $\sec^3 \theta$ for $\phi = 0$, but instead, to decrease slightly with deflection. In practice the increased effectiveness of the shielding toward the periphery or edge of the tube more than compensates the increase with deflection expected for a uniform magnetic field [which is less than given by Eq. (5.37) in view of the curvature of the screen].

In summary, the vertical field component produces a displacement of the landing points of the beam, which is reduced by the shielding of the tube. The shielding, however, also distorts the field so that some nonuniformity in the lateral displacement of the beam landing is produced.

5.3.3 Lighthouse Optics and Limitations for Printing Phosphor Screens

First-Order Printing and Lens Correction for Phosphor-Dot Screens

The screen of the shadow-mask tube, coated with a photosensitized slurry of one of the three phosphors, is printed by exposing the faceplate through the mask to a light source placed at or near the center of deflection of the beam (i.e., the intersection of the axis of the deflected beam with the axis of the undeflected beam, Fig. 5.15). This process is called first-order printing as distinguished from second-order printing which is described in Section 5.3.4. If the deflection center were invariant with deflection, the electron spots on the screen would also be centered on the electron dots; the registration of spots and dots would be perfect. The electron beams and corresponding light beams passing through the center of any one mask aperture would be identical in direction, and the resulting triad of electron spots would be centered on a triad of phosphor dots.

Unfortunately, as we have noted in Section 5.3.2, the deflection centers are not stationary. The properties of the deflecting fields are such as to cause them to move forward, toward the screen, with increasing deflection angle. Dynamic convergence, mentioned in Section 5.1, causes the centers

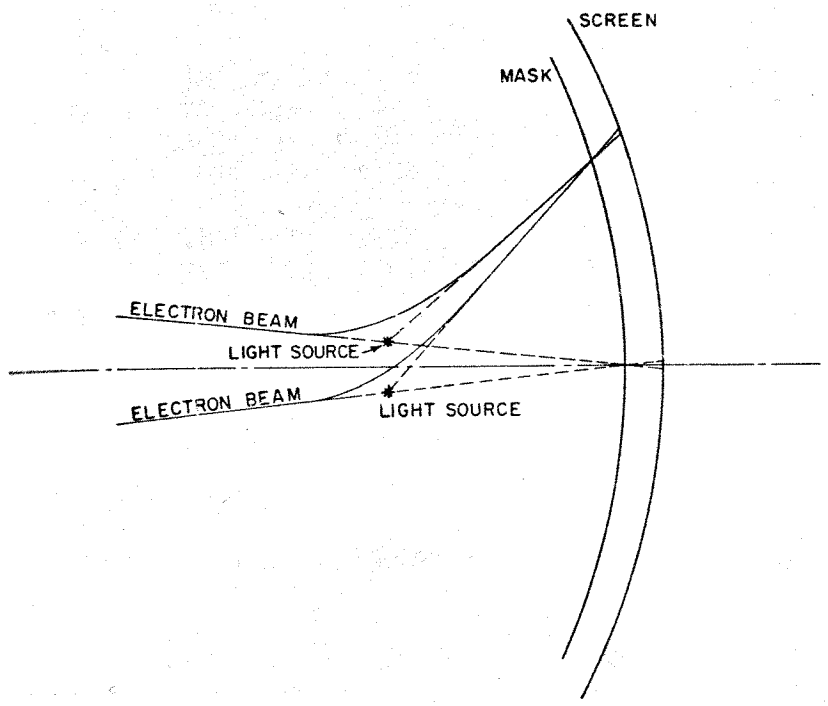

Fig. 5.15. Proper positioning of light source for first-order printing.

to move away from the axis. Finally, residual ambient magnetic fields, after magnetic shielding through which the beams pass, produce a displacement of the deflection centers from their position in the absence of the fields. The effects of these three factors are shown qualitatively in Fig. 5.16.

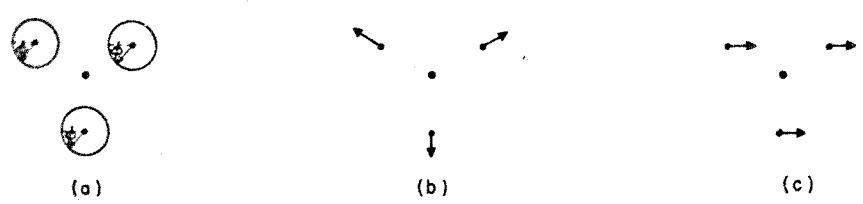

Fig. 5.16. Qualitative effect on apparent position of deflection centers in fixed plane of (a) forward motion of deflection centers with increasing deflection, (b) radial displacement of deflection centers by dynamic convergence fields, and (c) lateral displacement of deflection centers by vertical magnetic field.

Optical correcting elements are generally interposed between the light source and the mask to effect an apparent displacement of the light source corresponding to the displacement of the electron deflection center, or in other words, to cause the directions of the light beams incident on the mask-aperture centers to coincide with the directions of the corresponding electron beams. In this manner, improved registration between electron spots and phosphor dots may be achieved.

We shall now consider the form of the correction lens required. We shall assume that it has a flat back face, a perpendicular distance s_0 from an on-axis printing source (Fig. 5.17). At a point of the lens surface with the coordinates (x, y) we shall assume the lens to have a thickness $D(x, y)$ so that in polar coordinates we can write:

$$x = r \cos \phi, \qquad y = r \sin \phi \tag{5.38}$$

with

$$r = (s_0 + D/N)t, \qquad N = [n^2 + (n^2 - 1)t^2]^{1/2} \tag{5.39}$$

We write t for $\tan \theta_0$, where θ_0 is the angle of inclination of a light ray leaving the source and differs very little from the angle of deflection θ; n is the refractive index of the lens.

We assume the slopes of the lens surface to be very small. For any orientation of the incident light ray (t, ϕ) the lens acts as a combination of an infinitely thin prism with the vertex angle components $(\partial D/\partial x, \partial D/\partial y)$ and a plane parallel slab of glass of thickness D. As such it produces an ap-

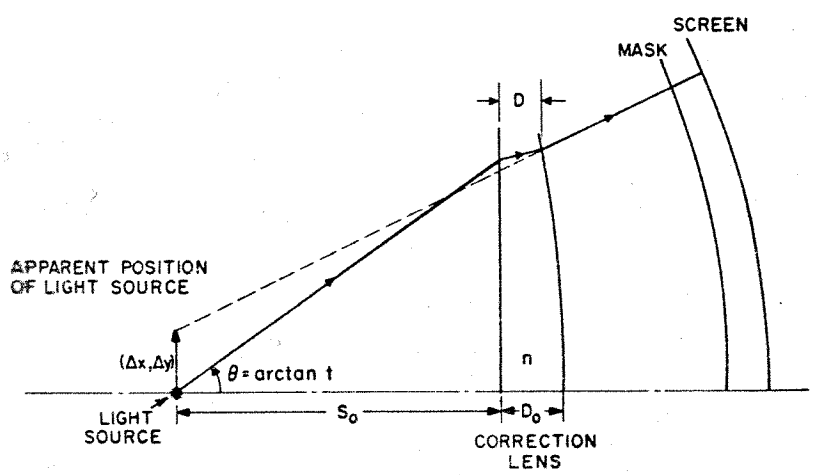

Fig. 5.17. Design of correction lens.

parent shift of the source in the source plane given by

$$\Delta x = -(N-1)\left\{(s_0 + D)\left[\frac{\partial D}{\partial x}(1 + t^2\cos^2\phi) + \frac{\partial D}{\partial y}t^2\sin\phi\cos\phi\right] + \frac{D}{N}t\cos\phi\right\} \tag{5.40}$$

$$\Delta y = -(N-1)\left\{(s_0 + D)\left[\frac{\partial D}{\partial x}t^2\sin\phi\cos\phi + \frac{\partial D}{\partial y}(1 + t^2\sin^2\phi)\right] + \frac{D}{N}t\sin\phi\right\}$$

Let the y direction coincide with the direction of displacement of the source from the tube axis, i.e., with the "s direction." Then perfect registration will be realized for

$$\Delta x = -(L_0 - L_0')t\cos\phi, \qquad \Delta y = -(L_0 - L_0')t\sin\phi + (s - s_0) \tag{5.41}$$

Here both $(L_0 - L_0')$ and $(s - s_0)$ are polynomials in t^2, as given by Eqs. (5.26) and (5.27).

If x and y are expressed in terms of t and ϕ, the first Eq. (5.40) becomes

$$\Delta x = -(N-1)\left\{\frac{s_0 + D}{s_0 + (t/N)(\partial D/\partial t) + n^2D/N^3} \times \left[(1 + t^2)\frac{\partial D}{\partial t}\cos\phi - \frac{s_0 + (n^2D/N^3)}{s_0 + (D/N)}\frac{\partial D}{\partial\phi}\frac{\sin\phi}{t}\right] + \frac{D}{N}t\cos\phi\right\}$$

$$\cong -(N-1)\left\{(1 + t^2)\frac{\partial D}{\partial t}\cos\phi - \frac{\partial D}{\partial\phi}\frac{\sin\phi}{t} + \frac{D}{N}t\cos\phi\right\} \tag{5.42}$$

The only approximation involved in Eq. (5.42) is that the separation s_0 is very large compared to the lens thickness D. For Δy we find similarly

$$\Delta y \cong -(N-1)\left\{(1 + t^2)\frac{\partial D}{\partial t}\sin\phi + \frac{\partial D}{\partial\phi}\frac{\cos\phi}{t} + \frac{D}{N}t\sin\phi\right\} \tag{5.43}$$

It is convenient to consider separately the lens required to compensate for the forward motion of the deflection plane [Eq. (5.26)] and that needed to correct for degrouping [Eq. (5.27)]. If these lenses are sufficiently weak and thin, their thicknesses may simply be added to form a single lens ac-

maximum residual registration error may be of the order of 1/3 of the maximum uncorrected degrouping error.

It should be noted that no improvement in the attainable degree of correction is to be anticipated from the use of a sequence of continuous lenses since the contribution of each of them is subject to the same limitations.

Lens Correction for First-Order Printing of Line Screens

In contrast to the dot screen discussed in the preceding section, a continuous-surface lens can be designed to completely eliminate printing errors in a phosphor line screen. In this case, a displacement of apparent source points parallel to the phosphor lines does not affect registration between the electron lines and the phosphor lines. A longitudinally extended source can advantageously be used for printing the screen. For an anastigmatic yoke the degrouping correcting lens (with zero center thickness) satisfying Eq. (5.43) can be described by

$$D_g(t, \phi) = c_1(t) \sin \phi + c_3(t) \sin(3\phi) + c_5(t) \sin(5\phi) + \cdots \quad (5.75)$$

For the specific degrouping characteristic given by Eq. (5.65) and a displacement along the phosphor lines (in the x direction) given by Eq. (5.66) the degrouping lens component is

$$D_g(t, \phi) = -\frac{(1 + t^2)^{1/2}}{2(N - 1)} b_1 t^3 \left[\left(1 - \frac{t^2}{3} + \cdots\right) \sin \phi + \left(\frac{1}{3} - \cdots\right) \sin(3\phi) + \left(\frac{t^2}{15} - \cdots\right) \sin(5\phi) + \cdots\right] \quad (5.76)$$

Here terms of the seventh and higher orders in t have been omitted.

The lens here described effects a source displacement in a direction normal to the phosphor lines exactly equal to the displacement of the electron source with deflection. The fact that, in the direction of the phosphor lines, it produces a small source displacement [given by Eq. (5.66)], which does not correspond to the electron source displacement, produces no printing error, if the printed phosphor lines are continuous. While the example here presented is specialized and the theoretical treatment given is limited in validity, the conclusion is generally valid: for the first-order printing of line screens, it is possible to design continuous degrouping lenses which eliminate the degrouping printing error if the phosphor lines are continuous. This follows from the fact that only one component of the source displacement, namely that producing a displacement perpendicular to the phosphor lines, must be the same for the light source and the electron source. Accordingly, only one component of the surface slope of the degrouping lens is prescribed over its entire area.

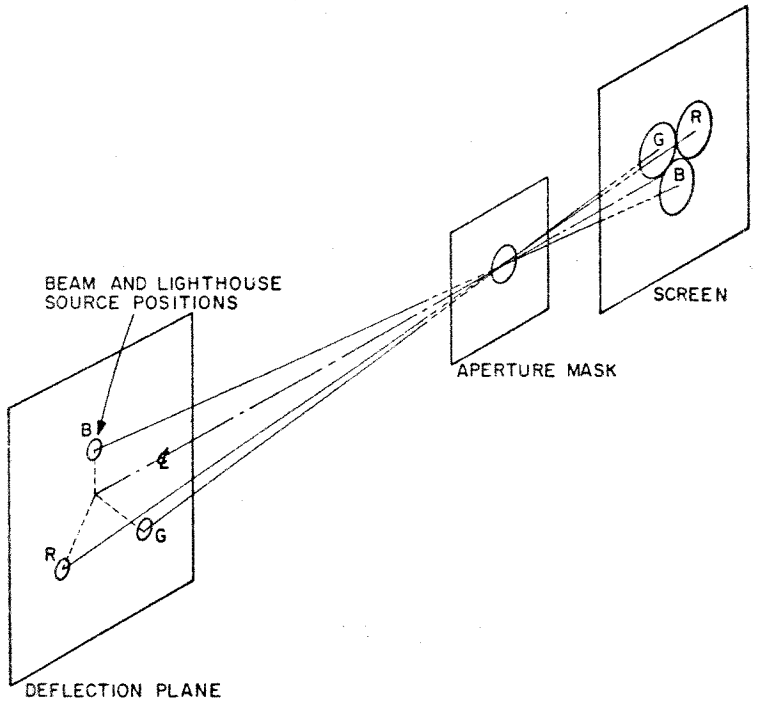

Fig. 5.21. Pictorial representation of first-order lighthouse printing.

Second-Order Printing and Lens Correction for Phosphor-Dot Screens

A different approach to the solution of the register problem due to degrouping is by the use of second-order printing. In the previous section, first-order printing was described. First-order printing may be defined as a printing technique wherein the light source is at, or approximately at, the position in the deflection plane in which the electron beam will appear in the finalized tube, as shown in Fig. 5.21. Second-order printing, however, differs in that the light source used for printing is not in the same location as the electron beam in the final tube, but rather is displaced a distance $3s$. As shown in Figs. 5.22 and 5.23, the displacement is such that a given phosphor dot is printed by exposing the light through the adjacent aperture in the shadow mask to that which will be used by the electron beam.

With second-order printing, as compared with first-order printing, separations of beam centers from the axis in the deflection plane are doubled and the red, green, and blue beam cross sections are rotated through 180°

about the axis. As a result, any triad of adjoining dots is produced by light beams passing through three different mask apertures surrounding the mask aperture utilized for forming the dot triad in first-order printing. This is shown more clearly in Fig. 5.23 where shading marks out the dots printed through the three apertures utilized for the central triad considered.

In Fig. 5.24 it can be shown that in second-order printing three light beams forming a triad will converge, whereas the three electron beams forming the corresponding dot triad diverge. Thus, the adjustment of q may be utilized to obtain a match in the relative size of the beam triad compared to the dot triad. This adjustment, therefore, is in effect a compensation for degrouping. Its limitation is that the degrouping for all three colors must be

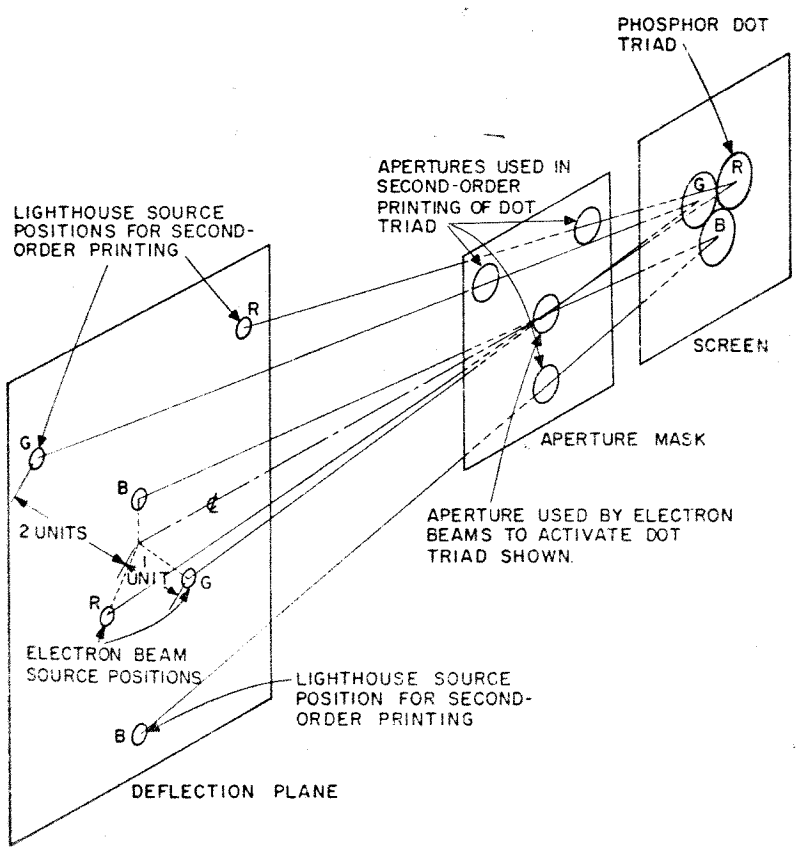

Fig. 5.22. Pictorial representation of second-order lighthouse printing.

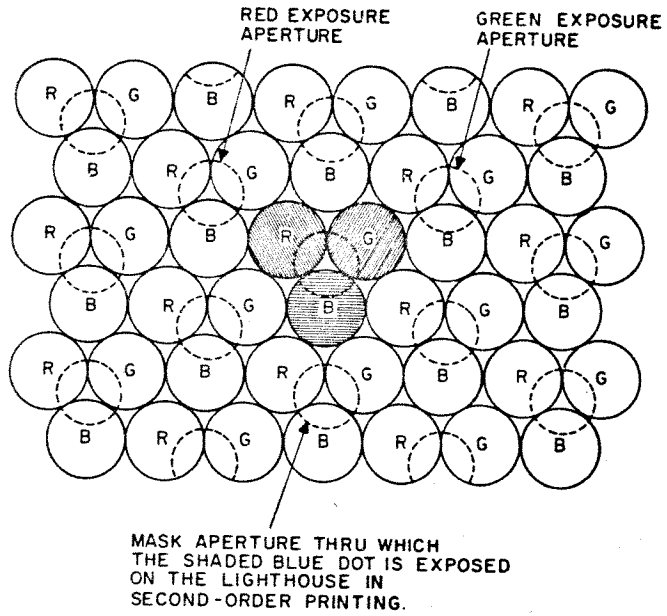

Fig. 5.23. Relation between mask apertures and dots printed through them in second-order printing.

equal in order to have complete compensation. In practice, due to yoke design considerations and foreshortening of dot triads, this is not always possible; however, it is possible to take the bulk of degrouping correction compensation in this manner.

In general, dynamic convergence produces a larger s value; that is, individual beams move away from the axis as the beams are deflected toward the edge of the screen. Therefore, in general, the electron beam triad is too large at the edge of the screen compared to the phosphor dots, hence the term "degrouping." If q is reduced near the edge of the screen, the electron beam triad becomes smaller, and conversely, the phosphor dot triad becomes larger. By selection of the proper value of q the average size of the beam triad and the dot triad may be made to coincide.

The q adjustment, which allows degrouping correction, has a drawback from a practical standpoint. Any variation of the q distance from optimum in tube manufacture will produce a register error. In first-order printing, a change in q will make both the electron beam and phosphor dot triad expand or contract but will not change the relative register between the two.

Hence, q variations with first-order printing will affect overall tube tolerance but will not affect register per se. It is, therefore, a choice between the improvement in the register obtainable with a continuous surface lens and the criticality of maintaining the q adjustment which establishes a relative merit of the two printing systems.

Pursuing further the correction of residual registration errors in second-order printing, it can be shown quite simply that a correction lens can be designed which, in principle, will make these errors vanish provided the deflection yoke has axial symmetry and is anastigmatic.

For an anastigmatic yoke the required degrouping component of the correction lens has the form of Eq. (5.67). Furthermore, if the aperture center pattern of the mask projected on a plane normal to the tube axis is a regular hexagonal pattern with aperture-center separation a, the separa-

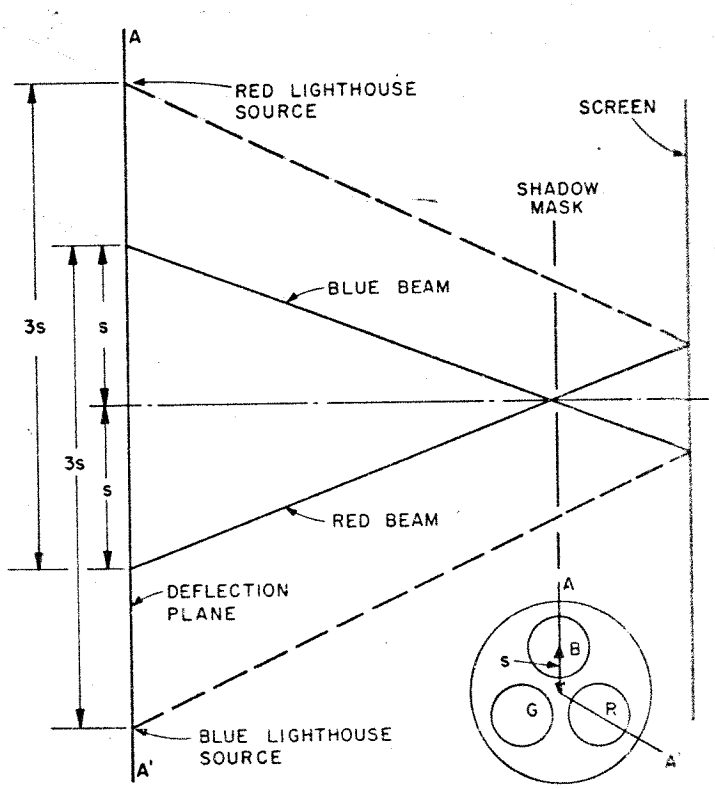

Fig. 5.24. Second-order printing geometry.

tion of the blue electron center from the blue light source center in the deflection plane (made coincident for the two by the radial lens component) is given by

$$\Delta y = a\left(\frac{\cos^2\phi}{m_t} + \frac{\sin^2\phi}{m_r}\right) - (s + 2s_0 - a)$$

$$= \frac{a}{2}\left(\frac{1}{m_t} + \frac{1}{m_r}\right) - (s + 2s_0 - a) + \frac{a}{2}\left(\frac{1}{m_t} - \frac{1}{m_r}\right)\cos(2\phi) \quad (5.77)$$

$$\Delta x = -\frac{a}{2}\left(\frac{1}{m_t} - \frac{1}{m_r}\right)\sin(2\phi) \quad (5.78)$$

Substitution of Eq. (5.67) in Eqs. (5.42) and (5.43) leads to

$$\Delta y = -\frac{N-1}{2}\left\{(1+t^2)\frac{\partial D_{gg}}{\partial t} + \frac{D_{gg}}{t} + \frac{D_{gg}t}{N}\right.$$

$$\left. -\left((1+t^2)\frac{\partial D_{gg}}{\partial t} - \frac{D_{gg}}{t} + \frac{D_{gg}t}{N}\right)\cos(2\phi)\right\} \quad (5.79)$$

$$\Delta x = -\frac{N-1}{2}\left((1+t^2)\frac{\partial D_{gg}}{\partial t} - \frac{D_{gg}}{t} + \frac{D_{gg}t}{N}\right)\sin(2\phi) \quad (5.80)$$

In Eqs. (5.77) and (5.78), m_t and m_r are the tangential and radial magnifications with which the deflection plane is projected through a mask aperture onto the screen, s is the distance of the electron deflection center from the axis, and $2s_0$ is the distance of the source from the axis. $m_t = q/p$ is proportional to q, whereas the ratio m_t/m_r is a function of t independent of the value of q. With Eqs. (5.77)–(5.80) we form:

$$\Delta y + \Delta x \cot(2\phi) = \frac{a}{2}\left(\frac{1}{m_t} + \frac{1}{m_r}\right) - (s + 2s_0 - a)$$

$$= -\frac{N-1}{2}\left((1+t^2)\frac{\partial D_{gg}}{\partial t} + \frac{D_{gg}}{t} + \frac{D_{gg}t}{N}\right) \quad (5.81)$$

$$\Delta y - \Delta x\frac{1-\cos(2\phi)}{\sin(2\phi)} = \frac{a}{m_t} - (s + 2s_0 - a) = -(N-1)\frac{D_{gg}}{t} \quad (5.82)$$

Substitution of a/m_t from Eq. (5.82) in Eq. (5.81) leads to the differential

equation in t:

$$\left(1 - \frac{m_t}{m_r}\right)(s + 2s_0 - a) = (N - 1)\left((1 + t^2)\frac{\partial D_{gg}}{\partial t} - \frac{m_t}{m_r}\frac{D_{gg}}{t} + \frac{D_{gg}t}{N}\right) \tag{5.83}$$

This equation can be integrated for the profile $D_{gg}(t)$ without specifying the variation of q. The latter is then established with the aid of Eq. (5.82):

$$q = pm_t = \frac{pa}{s + 2s_0 - a - [(N - 1)/t]D_{gg}} \tag{5.84}$$

Eq. (5.83) shows that the lens strength is proportional to $m_t - m_r$, i.e., to the radial foreshortening, as expected.

The derivation serves to demonstrate how the added degree of freedom resulting from the possibility of adjusting registration by variation of q permits greatly improved and, under specific circumstances, complete correction of registration errors with a continuous-surface correction lens. The compensating drawback, inherent in second-order printing, of great sensitivity of the registration to deviations from the prescribed q value, has already been noted.

In practice the lens design for second-order printing follows the same concepts as previously described where register data is taken and used to calculate the lens with the aid of a computer.

Discontinuous-Surface Lenses

There is still a third alternative to complete correction of degrouping errors that does not employ second-order printing (*54–56*). If first-order geometry is used, as has previously been shown, a continuous surface lens will not offer complete correction. However, within any given spot on the screen, perfect registration can be achieved merely by obtaining the desired thickness and slope of the lens to provide the proper dot placement. If such a procedure is followed for many small zones, each covering a small portion of the face of the tube, a close approximation to perfect register can be obtained. If this is done by dividing the lens into several hundred zones, the deviations in register between adjacent zones can be made rather small so that discontinuities from the edge of one zone to the beginning of another are relatively small. If, in addition, this lens is caused to vibrate or move during the exposure time so as to blend the adjacent zones together, the effect of the discontinuities can be minimized. Fabrication problems for lenses of this type are more complex than those of the continuous surface lens and, coupled with the need to move the lens during exposure, constitute the primary disadvantage of the system.

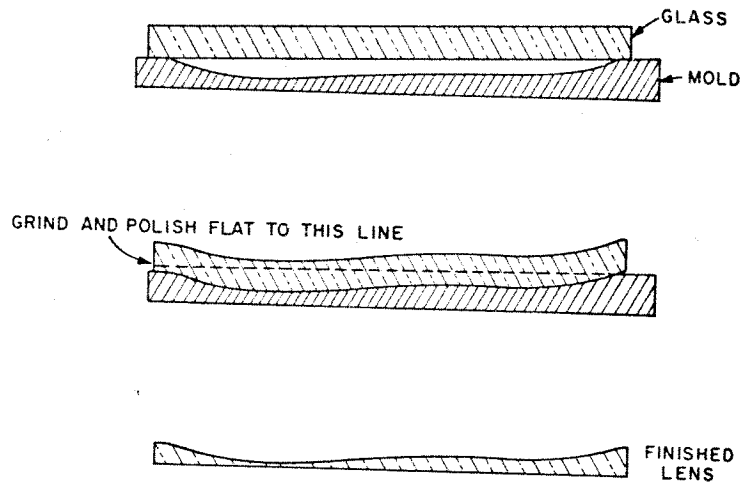

Fig. 5.25. Manufacture of correcting lens by sagging glass plate onto mold.

Fabrication of Continuous-Surface Lenses

Since the optimum continuous lighthouse correction lens seldom has a circular symmetry, its fabrication presents a unique problem. In general, two methods of fabrication have been employed. The first is a sagging technique and the second is a direct grinding technique. In the sagging technique, a ceramic or metal mold is very accurately cut by use of numerically controlled milling machines to the desired contour calculated for the lens. A plane, parallel, flat piece of optical glass is placed upon the mold and the temperature raised until the softening point of the glass is reached. The glass then sags or slumps into the mold, matching the contour of the mold. The upper surface of the glass, which is away from the mold, maintains its good optical finish and is used as the final contoured surface in the lens. The bottom surface of the glass, which was in contact with the mold, is ground in a subsequent operation to a flat surface. This fabrication system is illustrated in Fig. 5.25.

Direct grinding techniques have been employed wherein specialized high-precision numerically controlled grinding machines can generate the desired aspheric surface directly. With controlled polishing the surface may be brought to the proper optical finish. In either case, great skill is required to obtain a quantity of lenses within the tolerances required. In general, slope errors of the lens surface should be less than 1 mrad to meet the required commercial needs.

5.3.4 Phosphors

A phosphor suitable for shadow mask color use consists of a crystalline solid containing a small quantity of activator to produce and control the color of light emitted when the phosphor is struck by high-velocity electrons. Those of interest are limited to inorganic compounds since they must withstand heating to temperatures in excess of 400°C for an hour or more in an oxygen-containing atmosphere. In use, they must neither lose efficiency under prolonged bombardment nor evolve gas or other decomposition products that might adversely affect electron emission from the electron gun.

By today's standards, pictures on the first shadow-mask color tubes were dim; the red was particularly inefficient and required a didymium-glass filter to achieve the correct hue. Since then, the development of phosphors with improved chromaticity and greater luminance efficiency has been an important factor in improving color tube performance. At least 18 phosphors have been developed and successfully used in color tubes. A chronological listing by Hardy (*22*) has been updated to 1973 in Table II (*57*). The intense phosphor development activity, to which Table II attests, has resulted in an increase in basic phosphor screen efficiency from 15 up to

TABLE II

Phosphors (with Activator) Classified According to Color of Emission and Listed in Chronological Order of Commercial Use

Red:	1.	Cadmium borate : manganese
	2.	Zinc orthophosphate : manganese
	3.	Zinc selenide : copper
	4.	Zinc cadmium selenide : copper
	5.	Zinc cadmium sulfide : silver
	6.	Yttrium orthovanadate : europium
	7.	Yttrium orthovanadate : bismuth : europium
	8.	Yttrium oxysulfide : europium
	9.	Yttrium oxide : europium (limited use)
	10.	Gadolinium oxide : europium (limited use)
Green:	1.	Zinc orthosilicate : manganese (low conc.)
	2.	Zinc orthosilicate : manganese (high conc.)
	3.	Zinc aluminate : manganese
	4.	Zinc cadmium sulfide : silver
	5.	Zinc cadmium sulfide : copper : aluminum
Blue:	1.	Calcium magnesium silicate : titanium
	2.	Zinc sulfide : silver
	3.	Zinc sulfide : magnesium

35 lm/watt during the period 1951–1973. In this same period the shadow-mask tube device efficiency for producing white light, including device design improvements, has increased from 0.6 to 8 lm/watt (*57*). One such improvement of major proportions is the matrix screen described later in Section 5.5. Others relate to various design and manufacturing improvements that permit satisfactory tube operation with reduced screen tolerances so the mask transmission may be increased.

The colors produced by phosphors in use in 1973 are described in Fig. 2.2 by plotting the x and y coordinates of the phosphors on the CIE color diagram (*32*). As mentioned in Chapter 2 and shown on the diagram, white for color television receivers is currently adjusted to be near the center point of the diagram. If a straight line is drawn from the white point through any one of the three phosphor points (shown as crosses in the figure) and extended to the spectrum locus, the point of intersection on the locus is the dominant wavelength produced by that phosphor with that white setting. The ratio of the phosphor-point and dominant-wavelength-point distances from the white point gives the percent saturation of the phosphor. Similarly, straight lines drawn from the white point in any direction will define a dominant wavelength and a maximum attainable saturation for that hue determined by the intersection of these lines with the triangle joining the three phosphor points.

A significant new direction in phosphors for color television was taken in 1964 (*21*) by the replacement of red-emitting sulfide with the red-emitting, rare-earth yttrium vanadate : europium. All previous phosphors of all three colors have had broad emission bands with a half-value width greater than 40 nm. Rare-earth emitters are characterized by narrow-line emission from 0.1 to 0.5 nm wide. For equal energy output, and equal subjective color, narrow emission lines have a distinct advantage over broad bands for red because broad-band emitters in the red waste much of their emission at longer wavelengths where the eye is relatively insensitive (*58*). Figure 5.26 compares the spectral distribution curve of red-emitting zinc cadmium sulfide phosphor and red-emitting yttrium vanadate : europium phosphor. The same factors concerning line width obtain at the blue end of the spectrum, but line width is not of great importance in the green because the eye sensitivity here is high and has a wide distribution.

Improved red rare-earth phosphors have been developed since the introduction of yttrium orthovanadate : europium (*59–63*). In late 1973 the efficiency of the green-emitting phosphor was most in need of improvement to achieve approximate unity current ratios of the three beams to make white. Unity current ratio is desirable for two reasons. First, it would then be easier to match drive characteristics of the three guns to obtain a non-

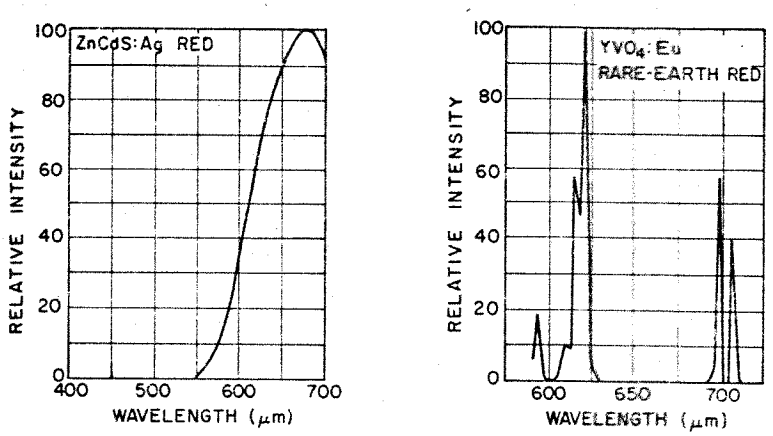

Fig. 5.26. Comparison of the emission spectrum from a broadband and a narrow line-emitting red phosphor.

varying white color temperature as a function of beam current or brightness. Second, brightness would be enhanced since each gun could then be used up to its capability of supplying current limited only by "spot blooming" instead of the limitation being set by the gun that is used for the weak phosphor. That is, if an increase in green-emitting phosphor efficiency can be obtained to bring the current ratios to unity (the red and blue efficiencies assumed to be the same), then the white light brightness would be increased by the same factor as the increase in the green-emitting phosphor efficiency.

5.3.5 Phosphor Application

The procedures employed for making a phosphor-dot screen by photodeposition will now be described (*6, 7, 13, 64*). Recent innovations going beyond these procedures to form black-matrix screens are deferred to Section 5.5. The first step is to coat the inner screen-substrate surface of the glass faceplate panel with a mixture of one of the primary color phosphors, an organic binder such as polyvinyl alcohol diluted with water, and a photoresist sensitizing agent that is usually ammonium dichromate. A machine is used to spin the panel face up, but tilted, while the mixture is introduced near the center and spreads to the edge. The machine then tilts the panel to a nearly vertical position, still spinning, to remove excess material. As the phosphor layer on the panel dries it becomes light sensitive and must be handled in a yellow safelight environment.

The mask associated with the panel is then inserted and the assembly placed face down on the lighthouse. Usually one lighthouse is adjusted to print one phosphor color, which means that the light source position is not changed after being placed at the desired color center as referenced to the panel. A second and a third lighthouse are used for the next two colors.

After exposing for several minutes, the mask is removed and the panel placed on an automatic developing machine. Here it is transported through a number of positions where a stream of water washes away unexposed phosphor and the exposed phosphor remains as a dot pattern. The delicate pattern is dried and is then ready for application of the second, and then the third, color dot pattern by repeating the operations for the first layer, using the lighthouse source at the proper location for each color.

An alternative to the above procedure is to coat the panel surface with photosensitized polyvinyl alcohol and, while it is still wet, dust it with dry phosphor powder to embed the phosphor into the layer. Exposure and development as before then produces the desired dot pattern (*65*).

Up to this point a number of problems may occur. There may be missing phosphor dots or incomplete removal of unexposed phosphor, which contaminates subsequent dots with extraneous color. Blocking of apertures in the mask by dirt is an ever-present problem that contributes to missing dots. The eye is very sensitive to irregularities in the dot patterns so that an unusually high degree of perfection is required. Literally, one missing dot in a million can be annoying if it is near the center of the picture. Such problems are solved by meticulous attention to detail in the production process.

The panel, with its array of three phosphor dot patterns, is next "filmed" with a thin plastic layer preparatory to aluminizing. One method is to wet the screen and then slurry an organic film-forming material, such as methacrylate, on the surface to bridge the openings between phosphor grains when the screen is dry. The plastic film then serves as a smooth substrate for an aluminum film that is evaporated on the organic film to form a continuous, light-reflecting layer. A well-made aluminum film can nearly double the tube brightness by reflecting back through the face of the tube light that would otherwise be lost.

The screen is then baked in air prior to tube exhaust to decompose or burn out the plastic film and all other organic matter left in during the screen-making process. The organic material is decomposed by an air bake to prevent copious release of gaseous products from the material when the tube is exhausted and baked out during processing.

A final process coming into use (1973) consists of applying a blackening layer on the gun side of the aluminum film to improve the screen's heat

absorption characteristic with only a negligible loss in light output. Such a layer improves the screen as a heat sink to help absorb heat radiated from the mask and prevent color distortion that results if the mask expands and moves out of position. Large color tubes with deflection angles greater than 90° are particularly sensitive to mask movement and benefit from the black layer.

5.3.6 Electron Guns

The high-performance objective of shadow-mask color tube guns and the restraints due to other factors have made the design of these guns a major challenge. As previously mentioned, because of the low shadow-mask transmission, only a small part of the electron beam energy is useful in producing light on the screen. This factor is somewhat compensated for by the use of three guns, whose beams must be carefully converged to achieve a useful picture at high brightness. For best resolution, anode voltages on the order of 20–30 kV, or higher, are commonly employed in shadow-mask tubes. Total average anode current of about 1 mA is common. Peak currents may be several times higher.

Physical space limitation, caused by the need to place three guns in a common neck, is a restraint on the diameter of the lenses that can be used and limits the electron optical performance of the gun. Use of a larger neck (larger gun-lens diameter) would help gun performance but would reduce deflection yoke sensitivity and make it much more difficult to properly dynamically converge the three beams. This gun-yoke performance trade-off has resulted in a situation where for increasing deflection angles the size of the neck, and therefore the corresponding size of the electron gun, has been kept inversely proportional to the deflection angle. For example, the 70° types commonly use a 51-mm diam neck, while the 90° types use a 36-mm neck, and many of the 110° types have 29-mm necks. As a result of a reduction in neck diameter with increase in deflection angle, there has been no great increase in deflection power with increase in deflection angle. The basic diameter of each of the electron guns is 12 mm for 70°, 9 mm for 90°, and 7 mm for 110°. These basic gun diameters have been obtained when the three guns are arranged in a delta fashion that allows a maximum size of electron gun per given neck size.

Figure 5.27 shows photographs of several electron guns commonly used in 70°, 90°, and 110° deflection shadow-mask tubes. The mechanical and electron-optical basic geometry is similar in each. In every case the electron guns are tilted toward the common tube axis at about a 1° angle. A precise angle is selected so that the beams will converge at the center of the screen. Generally the elements of the gun, including the cathode, control grid

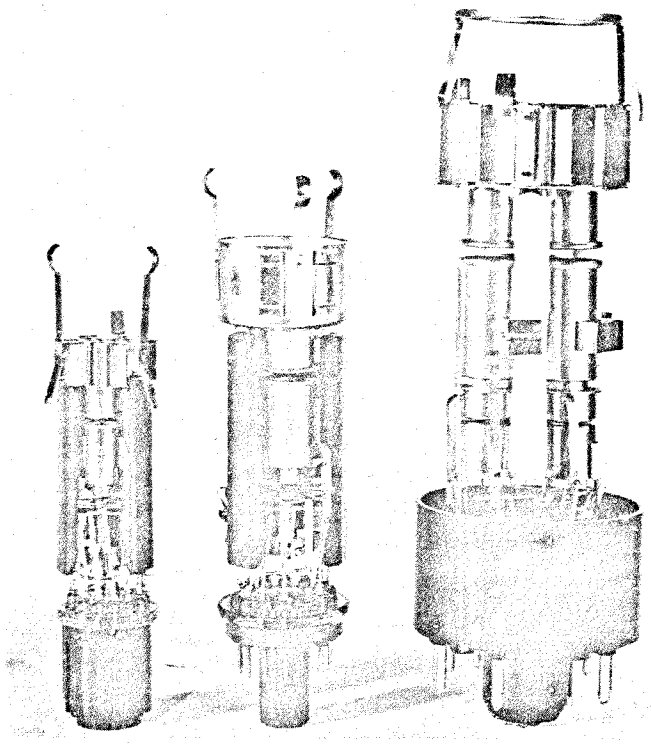

Fig. 5.27. Photograph of electron guns commonly used in 70°, 90°, and 110° shadow-mask color tubes.

(grid No. 1), grid No. 2 (G2), G3, and G4 or G5 are held by three glass multiform beads. For assembly, internal mandrels are used to hold the parts. They fit snuggly in the diameter of the grids and associated apertures and are mounted at the required convergence angle. Metal beading straps attached to the various gun elements are imbedded in glass beads that have been softened by heat. Straps from adjacent guns are attached to a common bead. In this manner, the six ends of the beading straps are imbedded in the three glass beads to provide a ruggedized triple gun assembly.

At the anode end of the gun an internal pole piece assembly is mounted. The assembly consists of three pairs of high permeability nickel-iron pole pieces with each electron beam passing between one pair of poles. The pole pieces extend to the glass neck and flare apart so that magnetic drivers can be coupled to them through the neck wall as shown in Fig. 5.28. The con-

figuration of the pole pieces is such that the magnetic flux lines are in a direction to deflect the electron beams radially. The purpose of the pole pieces is twofold: (1) to apply individual fields for convergence to each of the guns, and (2) to minimize curvature of the field by concentrating the magnetic flux lines, and hence, prevent electron beam distortion due to these fields. To minimize interaction between the three pole pieces, a Y-shaped shield of similar nickel–iron alloy is frequently placed between the pairs of pole pieces.

By use of a suitable external driver, a static magnetic field may be applied to correct center convergence to compensate for minor manufacturing variations in the convergence angle of the guns. In addition, a dynamic magnetic field is applied for edge or dynamic convergence.

To obtain complete static convergence of the three beams, a fourth degree of freedom is required. For this purpose an additional magnetic field is usually applied to the blue gun to move the beam in a direction at right angles to the movement provided by the dynamic convergence pole pieces. In some guns the field is produced by external means without use of internal magnetic structures.

Snubbers, for electrical connection of the upper elements of the gun to the neck coating and for mechanical centering of the top of the gun structure, are mounted on the mechanical assembly which houses the internal pole pieces. In addition, a ring-type getter may be mounted on this structure concentric with the mount, or more commonly, an "antenna" getter is

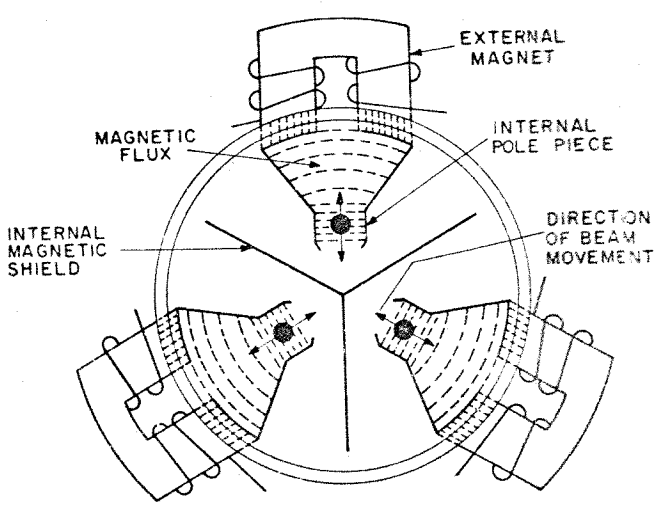

Fig. 5.28. Schematic of radial-converging pole pieces.

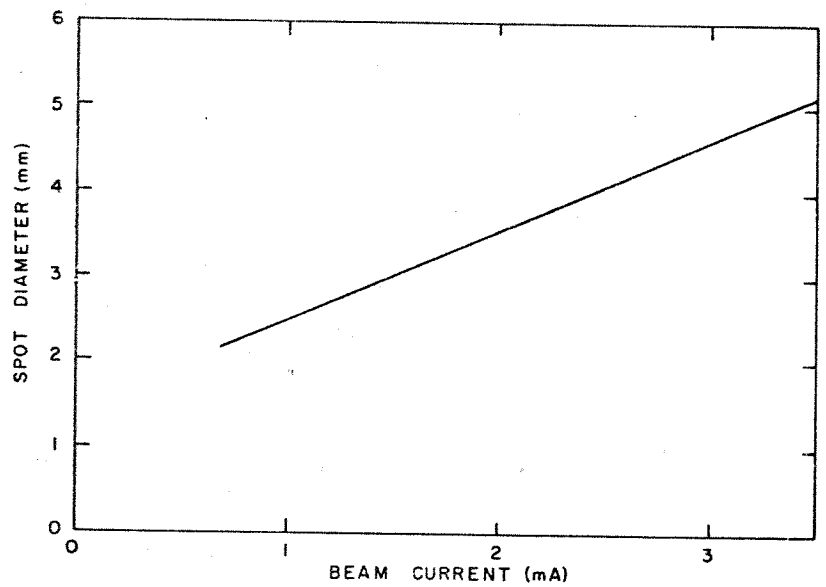

Fig. 5.29. 25V, 90° tube pulsed-spot average diameter vs beam current. Anode voltage 25 kV; focus adjusted at 1 mA; cutoff = −125 V.

slipped further up into the funnel portion of the tube by means of a long spring which fits snugly against the inner edge of the neck assembly.

Gun Performance

Turning now to performance characteristics of the electron guns in color tubes, spot size vs. current for a typical 25V, 90° tube is shown in Fig. 5.29. Spot profiles for several values of current are shown in Fig. 5.30. It is, of course, desirable that the spot size remain as small as possible with increasing current or the "blooming" in the highlights be a minimum.

In addition to a small beam spot size at the screen it is also important that the beam size in the deflection plane be kept to a minimum. There are two reasons: first, a large beam size in the deflection yoke may cause deflection defocusing, so that the spot size at the edge of the screen will be distorted and enlarged compared to that in the center; and second, the electron optics of mask shadowing at the screen makes a small beam size desirable. The following equation shows that the allowable transmission T of the shadow mask, for a given tolerance K at the screen, is a function of the ratio of the two variables s and m, s being the spacing of the electron beam from the central axis of the tube and m the size of the electron beam

in the deflection plane. The mask transmission T is given by

$$T = (\pi/18\sqrt{3})[\sqrt{3} - (m/s) - (K\sqrt{3}/R)]^2 \qquad (5.85)$$

where R is the diameter of tangent phosphor dots and the tolerance K is expressed as the difference in diameters between tangent phosphor dots and the diameter of that portion of the dot excited by the electron beam.

As was noted earlier, for deflection power reasons the neck size (therefore the gun size) and the s value have progressively decreased as the deflection angle has increased in the tube. In order to maintain high transmission of the shadow mask and suitable tolerances it has been necessary to try to maintain the value of m/s by reducing m as much as possible through electron optical design of the gun.

The majority of the guns used in shadow-mask tubes are of the bipotential type; that is, a main focus lens is formed between grid No. 3 (G3) and grid No. 4 (G4). G4 runs at the anode potential, typically 25 kV, while G3 runs at a voltage of about 18% of the anode voltage or about 4.5 kV with respect to cathode voltage. The G1 and G2 voltages are used to adjust the beam current and cutoff. Typically, G2 will be set at a value between 300 and 600 volts such that the cutoff voltage of G1 will have a value of 100 to 150 volts, negative with respect to the cathode. Under these conditions, the adjustment of G1 voltage, or cathode voltage with respect to G1, can produce a beam current up to 3–4 mA depending on the video drive applied.

Another type of gun, used primarily for the smaller screen sizes, employs einzel or unipotential lenses. In a gun employing an einzel lens, G3 is

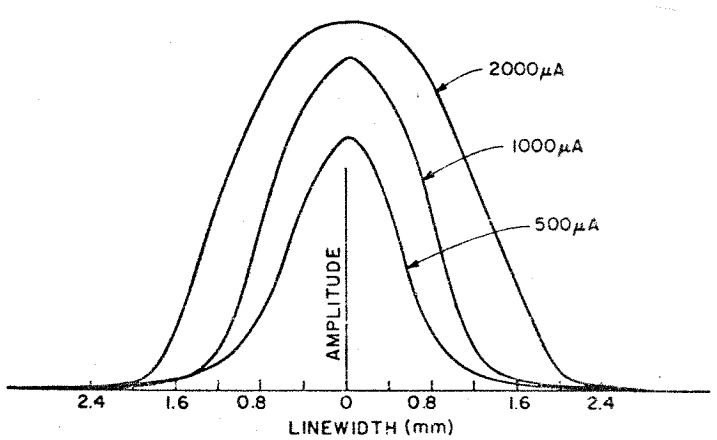

Fig. 5.30. Beam spot profile, 25V, 90° tube, anode voltage 25 kV.

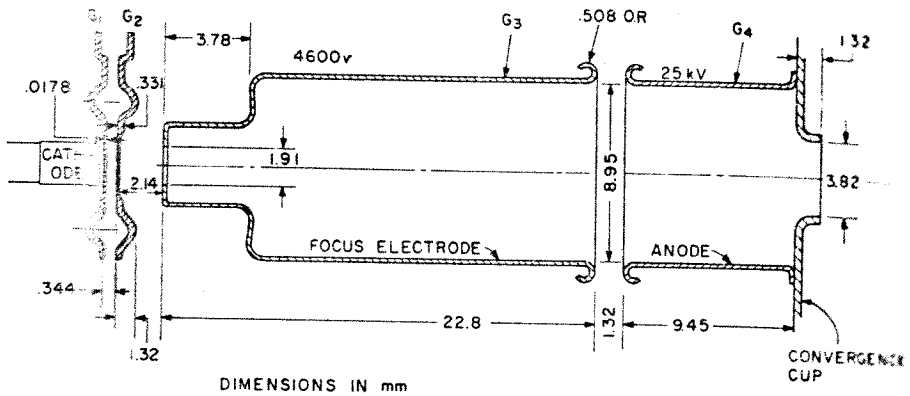

Fig. 5.31. Cross section of typical 25V, 90° gun. The apertures in G1 and G2 are 0.74 mm in diameter, and the cathode-G1 spacing when the cathode is hot is 0.11 mm.

electrically connected to G5 and run at anode potential. G4, between these two elements, is run at ground (cathode) potential or very close to it. The focus of the einzel or saddle lens is slightly less sharp than that of bipotential lenses. However, the einzel lens has the advantage that it does not require a second high voltage for the focus element since its potential is at ground, or within the voltage range available from the receiver. The high-voltage stability, or stability against arcing between electrodes, is somewhat less satisfactory in the einzel gun than in the bipotential gun because of the higher voltage gradient between elements of the gun.

The cathode in a typical gun is formed of a thin nickel cup enveloping the heater, with the end of the cup coated with emissive material. The cathode is operated at a temperature of about 1060°K and is normally insulated either by means of a ceramic disc mounted within the G1 cup or by a separate support element which is brought out directly to the beads, the beads providing insulation from the other elements. G1, having an aperture size varying from 0.6 to 0.9 mm, is shaped either as a cup or as a flat disc. G2, typically, has an aperture equal to or slightly larger than the aperture in G1 and is also either a flat disc or a small cup. G3 has an opening at the end toward the cathode which ranges from 1.5 to 5 mm in size; the main lens at the other end of the tubing is the full diameter of the tubing. G4, the other half of the lens, is normally of similar size and the gap between G3 and G4, typically, is 1–1.25 mm with carefully smoothed and rounded edges to prevent localized high-voltage gradients. Figure 5.31 shows a cross section with the dimensions of a single gun taken from a typical 25V, 90° tube.

Some shadow-mask tubes employ in-line guns wherein the three electron beams are generated in the horizontal plane, side by side. One in-line gun employs the individual delta guns in a line rather than a delta cluster. A gun of this type is shown at the right in Fig. 5.32. In another in-line gun structure, a single large main-focus lens is used for all three electron beams (*24*). In the center photograph of Fig. 5.32 such a structure is shown. In this system the three guns are tilted so the beams leaving the cathode-G1-G2 region cross in the center of the main-focus lens. Then, after being focused by this lens, the outer beams diverge from the center beam and are later bent back by an electrostatic convergence assembly so that they meet at the screen. In this type of structure, in addition to the voltages required for the formation of the electron beam in the individual guns, an additional high-

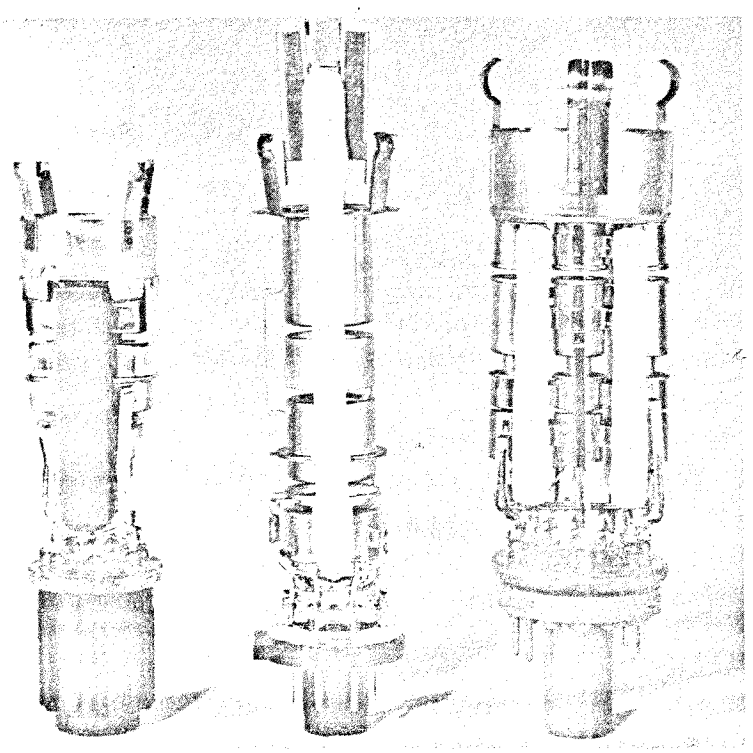

Fig. 5.32. The in-line gun on the left employs unitized construction (RCA precision in-line). The gun in the center has a single main-focus lens for the three beams (Sony in-line gun). On the right is an in-line gun with individual-barrel construction (General Electric).

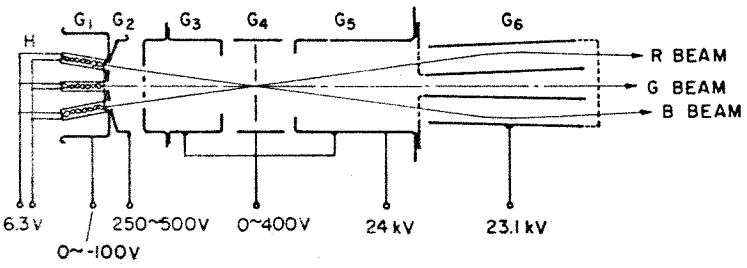

Fig. 5.33. Line drawing of in-line gun with single main-focus lens (Sony).

voltage connection is required for the convergence assembly. Details of this in-line gun structure are shown in Fig. 5.33. A shorter version of this gun has been developed for tubes with deflection angles greater than 90°. The shorter gun-to-screen distance resulting from wider deflection angles, coupled with the large-diameter focus lens, favors formation of a small spot, particularly in the central part of the screen (*66*).

A third type of in-line gun structure, shown at the left in Fig. 5.32, is one in which the guns are combined into one mechanical assembly and the separation of the beams is by means of individual apertures within the common gun electrodes. This is shown in Fig. 5.34. Since the cathodes are the only elements of the gun that are electrically separated between guns, the three color signals must be applied to the three separate cathodes. G1 and G2 have common plates with triple apertures, giving very good alignment between the gun elements. G3 and G4 are similarly constructed. The unique self-converging yoke used with this gun makes provision for dynamic converging elements unnecessary, as described in Section 5.6.1 on in-line deflection systems.

5.3.7 Shadow Masks

The shadow mask is one part of a color tube that has no counterpart in a black-and-white picture tube. The apertures are made by etching thin flat mask metal from both sides at the same time. Technological development of the mask has been a major undertaking that has involved fabricating dot-pattern artwork with unusual dimensional tolerance requirements which are needed to produce very close geometric control of the mask itself. At first the hexagonal-array dot patterns were generated by manipulation of very accurate line rulings; but later, patterns were made by skillfully using very accurate computer-controlled plotting equipment.

Coils of low-carbon steel strip, 0.15-mm thick and left hard-as-rolled, are coated on both sides with glue photoresist. Still in coil form, the metal is

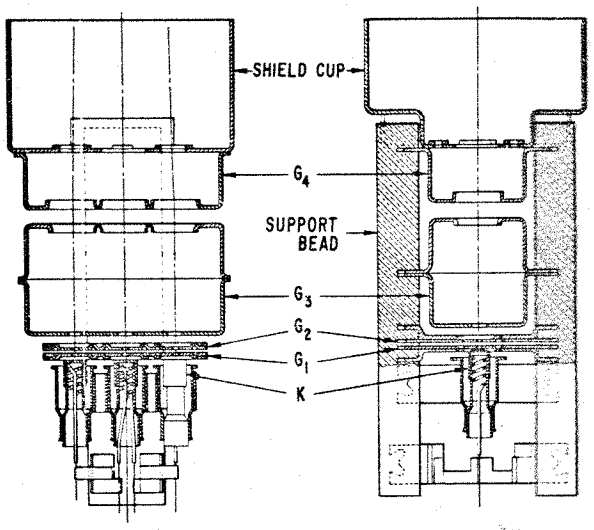

Fig. 5.34. Line drawing of in-line gun with unitized construction (RCA).

exposed to light on both sides using registered patterns of opaque dots and clear border area to produce a resist pattern with holes in the resist where the apertures are to be etched. The dot openings in one pattern are much smaller than the corresponding dots in the pattern on the reverse side. The coil of metal is now etched from both sides at the same time with a forceful spray of hot ferric chloride until apertures of a precise size are produced in the metal.

Figure 5.35 shows the cross section of an aperture produced with the resist still in place. The combination of a larger opening in the resist on one side and a higher etchant spray pressure produces a defining knife-edge aperture located near the other face of the metal containing the small resist openings. In the picture tube, this knife-edge side is placed toward the gun so that a minimum number of scattered electrons, produced by beam elec-

Fig. 5.35. Aperture etched in shadow-mask with photoresist still in place. The surface of the mask with the small opening faces the gun.

trons striking the sidewalls of the apertures, can reach the screen to degrade color saturation and picture contrast.

After etching and resist removal, the masks are torn out of the coil at a half-etched-through boundary line and then annealed. After annealing, the masks are roller-leveled or flexed to break up large crystal structures and then formed to an approximately spherical contour, including a turned edge or skirt to facilitate welding the mask to a frame. Great care must be taken in forming because uniform stretch of the metal is very desirable to prevent aperture pattern distortion. Also, it is necessary that the prescribed contour be accurately produced since the mask-screen spacing, which is critical, is directly affected.

In a final process the mask is treated to obtain a black iron-oxide coating that forms a chemically stable surface with good thermal emissivity. Emissivity is important because heat generated in the mask by the electron beam must be largely dissipated by radiation. If the mask temperature rises excessively, thermal expansion of the mask will cause color impurity (*18*).

5.3.3 Mask Support

In the process of fabricating the phosphor screen of the color picture tube, the mask must be removed from the panel assembly several times during the scanning process. Typically, replaceability errors of greater than 5–10 μm cannot be tolerated for an assembly design to be practical. In addition to the replaceability requirement, the mask-panel system must go through thermal cycles up to 400°–450°C for frit seal and exhaust bake and then return to the original position relative to the screen on the faceplate that it had during the screening operations.

To meet these requirements, the mask is normally mounted on a rigid metal frame and the skirt of the shadow mask is welded to the sidewall of the frame at numerous points around the periphery. The cross-section thickness of the frames used for mounting typical shadow masks range from 1 to 3 mm. In general, they have an L section; in some cases this L is modified by reenforcing gussets or other features. These frames may be fabricated either by a forming operation or by a wrap-and-weld operation. The forming operation allows complete freedom to use a frame with variable cross section of the frame; however, it has the economic disadvantage of wasting material. A wrapped-weld frame is normally made from metal with a constant cross section which is formed into the rectangular shape and the ends of the frame butt-welded. The combination of the shadow mask welded to the frame usually provides a rigidity to the assembly that is substantially greater than that of either frame or mask individually.

The mounting of the mask frame into the panel is achieved by means of tapered-metal studs, which are secured to the glass sidewall of the panel,

and leaf springs welded to the mask frame, each of which has a hole that engages a tapered stud. Such a system of leaf springs and studs as shown in Fig. 5.36 has been used almost universally in all color picture tubes, starting with the 70° round types and then extending into all of the 90° and 110° rectangular types. The metal stud, which is heat-sealed to the side of the glass bulb, is about 6 mm in diameter and employs a tapered end with a 12° angle. The leaf spring is normally made of steel and has either a round

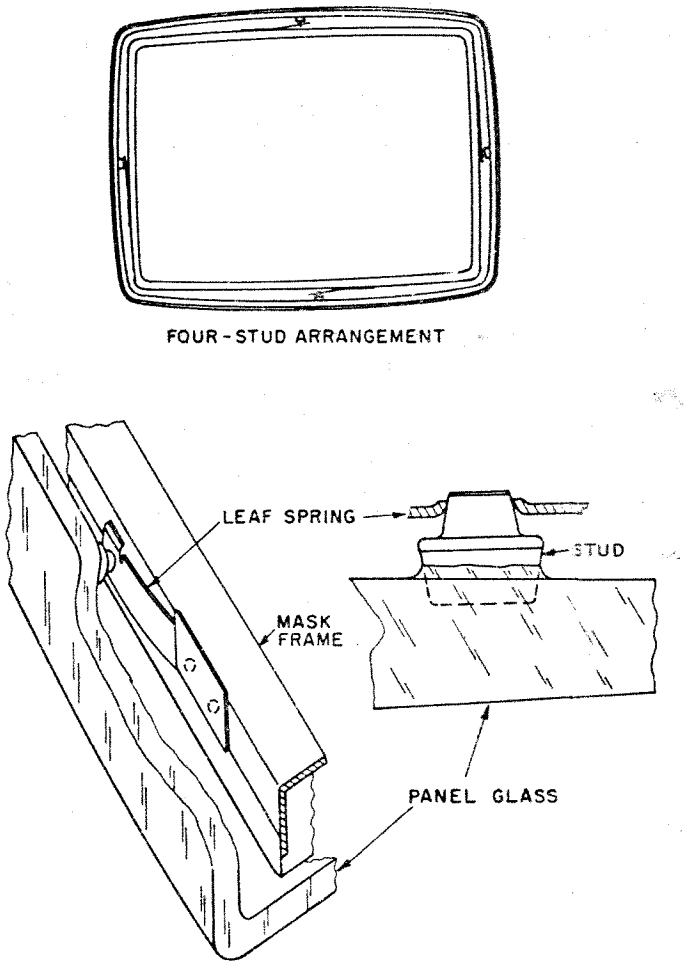

Fig. 5.36. Four-stud leaf-spring arrangement used to hold mask-frame assembly in the bulb panel. Typical studs are shown with a leaf spring design that does not have temperature compensation.

or a slightly triangulated hole in the end to engage the tapered portion of the stud. This triangulation of the hole, or various versions of tapering of the hole, is made so the contact area on the taper is stabilized at the minimum number of points. Flexing of the springs allows for differential thermal expansion during the heat cycles required for tube processing. The panel glass has an expansion coefficient of 99×10^{-7} per °C while that of the frame is typically 130×10^{-7} per °C. Therefore, even with slow thermal cycles a mismatch in size of glass and metal parts of 0.75 mm occurs at peak temperature.

In round tubes, three studs placed approximately 120° apart are used for the support mechanism. This in essence gives a three-point support system which is unique and self-setting; but, upon closer examination, one finds each of the three points has multiple points of contact onto the stud, so that the problem becomes slightly more complex than would seem initially. With the introduction of rectangular bulbs, the same stud system was employed, with some manufacturers continuing to use three studs, and others using a four-stud system. With the three-stud rectangular bulb, the symmetry of the round tube does not exist in that the angular separation of the three studs is no longer 120°. In this case, one stud is normally placed at the top or 12 o'clock position of the panel and two additional studs are placed on either side, somewhat below the center line of the panel. In this system, the same unique three-point system is maintained and therefore the placement of the mask within the panel is relatively simple. In the larger sizes particularly, a disadvantage is the considerable overhang of the frame from its support system and therefore a heavier, more rigid, frame is needed to prevent motion. A further disadvantage is that the center line of the system of the three studs no longer coincides with the geometric center of the mask.

In a four-stud system, the studs are usually located on the major and minor axis of the rectangular bulb; that is, at 12 and 6 o'clock, and 3 and 9 o'clock. With this system, a somewhat lighter frame can be used and the symmetry of the support system is maintained in that expansion of the parts takes place around the center of the system. The disadvantage is that seating of the fourth spring on its stud in the four-stud spring system is no longer automatic. The fourth spring position is uniquely determined when the first three are engaged, so great care must be taken in placing the springs if all four are to give proper support.

Control of Mask-to-Screen Spacing

The spacing, q, between the shadow mask and the faceplate on which the screen is printed, must be controlled very precisely. The typical value of q

is between 8 and 15 mm, depending on the tube size and geometry. Deviations from the design value must be held to within 0.4–0.5 mm. In order to achieve this accuracy the contour of the faceplate must be controlled, as discussed in Section 5.3.9, and the forming of the metal shadow mask must be held to very tight tolerances.

To obtain the proper spacing, various systems of q-setting have been used with a three-stud support system. The studs are normally located accurately in the envelope in relation to the face contour and then placement of the springs on the mask frame assembly can be done in a jig which holds the mask against a contoured metal gauge. The relationship of the springs is established by placing the holes on dummy studs located in the same spatial relationship to the gauged contour of the mask. In this manner, the springs may be welded and when the assembly is placed within the glass panel the q will be held to required tolerances.

A second system which gives somewhat tighter tolerances is to individually set q within the panel where it will be used. In this system a spacer, placed on the glass faceplate surface, is precisely of the thickness required for the q-spacing in the finished assembly. The mask is then placed into the panel and rests on the q-spacer. Thus, with the unique spatial requirements established for that particular panel, the springs are then welded to the frame, or to a second member or clip in order to prevent the welding guns from getting too close to the glass side wall of the panel. This system is also useful for the four-stud approach because then the springs are placed uniquely in relation to the four-studs and the tailored relationship is maintained.

A somewhat different system of q-setting can be employed by delaying the welding of the mask to the frame until the final step. In this system the springs are welded to the frame in a jig and the q-spacer placed in the glass panel. The frame is then placed into the assembly, with the springs engaging the studs. The final operation is to weld the skirt of the mask to the frame, q being set by the q-spacer.

Electron Shield

In a typical mask-frame assembly, see Fig. 5.36, there is a 6–8 mm space between the edge of the frame and the inner side wall of the glass panel. In tube operation, if nothing further is done, the overscanned electron beam could enter into this space between the frame and the side wall and ricochet or bounce onto the faceplate. These electrons do not pass through the mask and therefore flood the entire screen in an uncontrolled manner, generating light of incorrect color and high intensity around the periphery of the screen. To prevent this, a thin metal electron shield is spot-welded to the

frame at final assembly to close the gap between the mask frame and panel. In addition to the flat electron shield, some manufacturers have employed a formed aluminum shield which is tucked down between the frame and the sidewall to form a somewhat tighter seal for complete elimination of electron strays on the screen. An added advantage of this shield is its greater degree of flexibility when the assembly goes through heat cycles. The contact of the shield to the glass is weak enough that it does not cause a distortion or a misplacement of the mask assembly in relation to the panel.

The inner sidewall of the mask or frame can also provide an area on which overscanned electrons may be reflected back through the shadow mask onto the screen. These electrons would be generated from a point other than their color center and would scatter over all three phosphor colors of the screen. To minimize electron reflection, the L section of the frame is designed to mask the majority of these electrons.

Temperature Compensating Mask Mounting

As we previously mentioned, the expansion of the mask frame assembly due to electron bombardment of the mask during tube operation will adversely affect screen register. Figure 5.37 shows how misregister is caused by thermal expansion of the mask. For any radius r_p, the outward radial misregister M_r (for concentric mask and screen) can be predicted by the following equation:

$$M_r = \left(1 + \frac{q}{p}\right) \Delta R \left(\frac{\cos \beta_e \sin \theta - \sin(\theta - \beta)}{\cos(\theta - \beta)}\right)$$

where p is the mask-to-deflection plane spacing along the beam path; q is the mask-to-screen spacing along the beam path; β is the screen inclination angle; β_e is the screen inclination angle for a beam path intercepting the formed mask edge; θ is the beam deflection angle; and ΔR is the thermally induced change in the mask radius of curvature corresponding to: R_m, the mask radius of curvature; α, the coefficient of thermal expansion; and ΔT, the change in mask temperature.

The center-to-edge distribution of the outward aperture shift produced by the expanding dome can be compensated for all radii by a uniform movement of the mask parallel to the tube axis, as illustrated in Fig. 5.38. The axial motion of the assembly Δq is a function of the thermally induced change in the mask radius of curvature (obtained from Fig. 5.37) and other parameters based on the particular tube geometry, and not on the beam deflection angles.

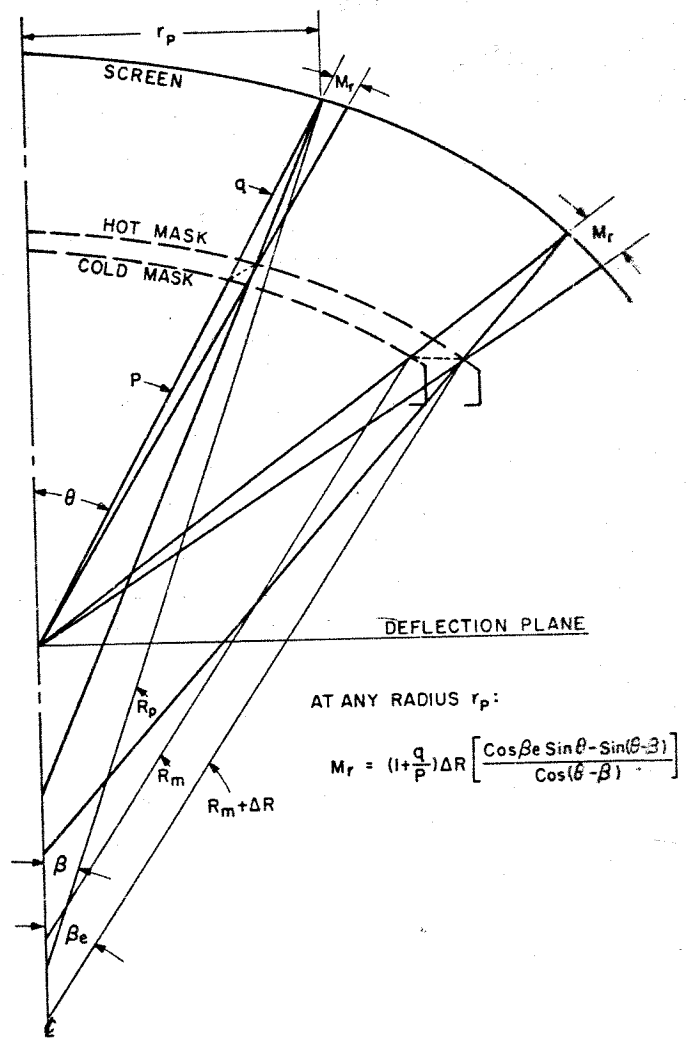

Fig. 5.37. Diagram showing thermally induced radial misregister.

This movement of the mask assembly toward the screen as it heats up may be obtained by use of bimetal elements. They may be mounted between the frame and the leaf spring or they may be the spring itself. A commonly used bimetal element is shown in Fig. 5.39. In the example shown the bimetal element employs a tapered loop that amplifies the

movement. The arrow shows the direction the assembly moves as the bimetal elements heat.

An example of typical misregister produced with and without this type of compensation is shown in Fig. 5.40. Some type of bimetal compensation is used in the majority of color picture tubes.

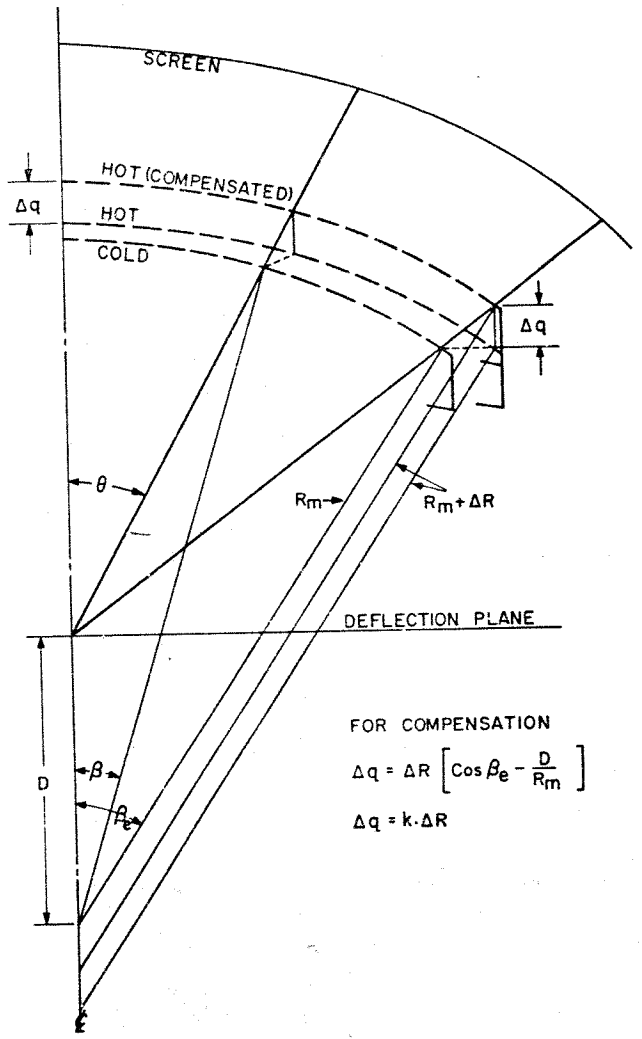

Fig. 5.38. Diagram showing that thermally induced radial misregister can be substantially compensated for by a uniform axial movement of the mask assembly toward the screen.

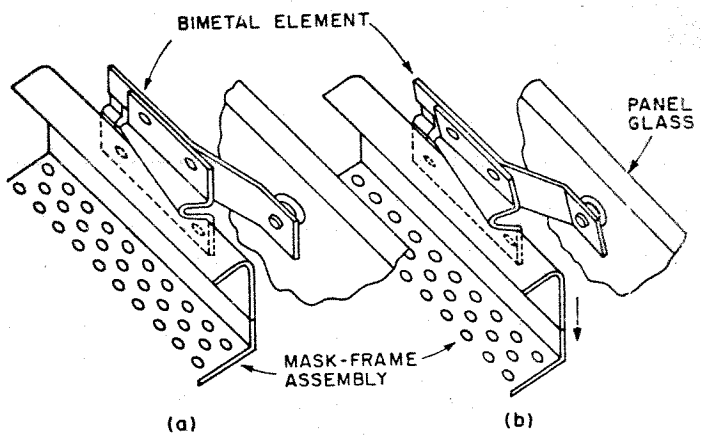

Fig. 5.39. Bimetal element providing axial movement of the mask-frame assembly to compensate for misregister caused by electron-beam heating of the mask, (a) unheated and (b) heated with arrow showing direction of motion.

5.3.9 Color Tube Bulbs

An extensive amount of bulb design work and development of manufacturing processes has been necessary to satisfy color bulb requirements while at the same time keeping the cost of the bulb at a reasonable level. As an indication of the importance of bulb cost, more than half the value of a color tube lies in the bulb itself. Specific information about requirements of the color bulb and a discussion of other features of the bulb will now be given, including a list of commercial color tube dimensions and weights by type as of 1973 which will be found in Table III.

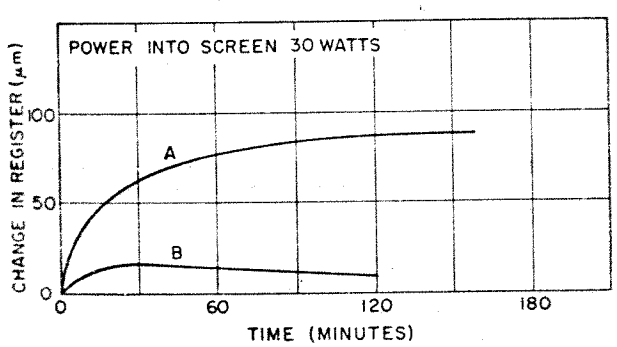

Fig. 5.40. Average thermally induced misregister at the screen corner for a 25 V rectangular picture tube. Curve A is for no compensation; curve B, with compensation.

TABLE III

COMMERCIAL COLOR PICTURE TUBE DIMENSIONS AND WEIGHTS (MAJOR TUBE TYPES AS OF 1973)

Type (Screen diag. to closest in.)	Screen dimensions				Outside tube dimensions				Weight (kg)
	Diag. (mm)	Horiz. (mm)	Vert. (mm)	Area (cm^2)	Diag. (mm)	Horiz. (mm)	Vert. (mm)	Length (mm)	
Types manufactured in the United States									
90° Deflection, delta gun, 36-mm neck diam.									
25V	626.3	527.7	395.8	2032	666.7	571.8	442.5	549.4	20.4
23V	584.1	504.8	395.6	1903	624.0	546.1	438.5	530.9	17.9
21V	530.1	445.5	336.7	1458	564.2	484.3	379.8	483.5	14.2
20V	513.9	443.1	346.5	1465	551.7	482.0	367.0	488.0	13.8
19V	480.0	404.4	303.3	1194	513.5	440.5	341.8	463.5	11.4
18V	459.1	395.9	309.5	1161	493.3	431.2	347.1	458.6	10.7
17V	432.3	364.2	273.2	968	471.0	405.7	315.8	434.9	10.2
16V	411.3	354.4	276.9	935	441.7	385.8	309.6	426.7	8.3
14V	344.4	296.0	232.1	658	374.5	327.7	263.9	386.1	5.4
110° Deflection, delta gun, 29-mm neck diam.									
25V	626.3	527.7	395.8	2032	666.7	571.8	442.5	432.0	19.6
19V	480.0	404.4	303.3	1194	513.5	440.5	341.8	368.1	10.9
90° Deflection, in-line gun, 29-mm neck diam.									
19V	480.0	404.4	303.3	1194	513.5	440.5	341.8	417.0	11.4
17V	432.3	364.2	273.2	968	471.0	405.7	315.8	388.4	10.2
15V	382.3	322.1	241.6	755	417.2	359.0	280.2	360.6	7.1
13V	334.8	282.0	211.5	581	367.1	316.0	247.5	332.1	5.4

Types manufactured in Europe and not previously listed									
110° Deflection, delta gun, 36-mm neck diam.									
24V	617.8	518.0	390.0	1966	657.6	556.4	435.3	431.6	20.0
21V	533.0	447.0	337.0	1466	574.0	495.0	391.0	—	—
Types manufactured in Japan and not previously listed									
90° Deflection, delta gun, 36-mm neck diam.									
13V	335.4	280.8	210.6	581.2	372.9	317.9	248.9	366.5	6.0
12V	295.2	254.5	199.0	473.0	367.1	300.2	246.5	352.3	4.8
11V	284.0	245.0	191.0	455	314.0	279.0	226.0	355.0	3.6
90° Deflection, in-line gun, 29-mm neck diam.									
12V	302.0	245.0	192.0	463.7	377.0	294.0	246.0	366.3	4.7
9V	228.6	192.6	144.5	268.9	266.1	230.0	179.1	287.0	—
110° Deflection, in-line gun, 36-mm neck diam.									
19V	480.0	404.4	303.3	1190	513.6	440.5	341.8	368.5	11
110° Deflection, delta gun, 29-mm neck diam.									
17V	432.2	364.2	273.2	968	468.8	402.9	312.3	337.0	—
114° Deflection, in-line gun, 29-mm neck diam.									
17V	438.4	357.0	272.5	934.2	479.0	400.0	325.0	337.2	11.2

Color tube bulbs are characterized by several factors:

(1) They are made of harder or higher softening-point glass than for black-and-white bulbs to minimize deformation during thermal processing. The panel glass typically has a strain point of 462°C, annealing point of 503°C, and a softening point of 688°C.

(2) Constituents such as strontium, lead, and barium are used in making the glass panel for absorption of practically all x rays which otherwise would be transmitted through the face of the tube. At the same time, the composition must also be selected to minimize browning effects in the glass caused by these x rays or by the electron beam.

(3) Three alignment pads or reference points are molded on the panel and on the funnel to align the two during the seal, and prior to sealing, as reference points in printing the phosphor screen in the desired location. The reference points are also used to align the gun in the neck for gun-seal which takes place after the panel-funnel seal.

(4) Three or four metal studs are placed on the panel wall to hold the mask-frame assembly.

(5) The inner contour of the faceplate is normally held to a tolerance of 0.43 mm from its prescribed position. This contour is normally measured either from the metal studs or from several selected points on the face contour itself. The achievement of this tolerance has been a major factor in the development of successful color tubes. Considering that this tight tolerance is maintained over an area of about 2000 cm^2, it is an achievement not obtained elsewhere in the glass industry in mass-produced commercial products.

(6) In addition to the tight tolerance on the faceplate, the neck assembly must be aligned so that it is perpendicular to and coaxial with the face. Special jigging is used to obtain perpendicularity of the neck to the seal edge of the funnel during its fabrication. In a further step, the sealed-on neck is held in a jig for precise positioning of its center line. The three pads located near the seal edge are ground to be a precise distance from this center line. By this procedure eccentricity of the neck in relation to the true center of the bulb system is held to less than 0.25 mm. This procedure is necessary so that the deflection center of the electron beams in the final tube will lie at points very close to the light source used in the lighthouse when the phosphor screen is printed; however, minor compensations for lack of coincidence can be achieved by means of the magnetic purity device on the neck of the tube. This device deflects the beams a small amount so as to aim them at the prescribed deflection centers and therefore produce corresponding pure colors on the tube face.

(7) The periphery of the seal edge of the panel and the funnel must be closely controlled so that maximum engagement of the two parts is achieved during the frit-sealing operation. Numerous points around the edge are carefully controlled so that the entire bulb assembly will have an engagement of sufficient width to insure a satisfactory seal. Typically this value is 10 mm or greater.

The thickness of face glass and funnel glass used in the bulb design must provide stability of the glass parts and also sufficient pressure strength for the bulb. Upon evacuation of the picture tube, air pressure exerts a force exceeding two tons on the face of the 25V tube. By proper design, stresses are kept at such low level that the possibility of breakage of the glass is negligible. Typically, a glass bulb used for a color picture tube will withstand 3 atm of pressure before breaking. This, in essence, gives a safety factor of three to the tube.

Stringent safety requirements have been set up by various agencies to guarantee that no harm can come to the user of a tube from inadvertent striking of the glass bulb. Since the face is naturally exposed in the final television receiver, this is most important. Test criteria of pendulum implosion test procedures have been prescribed so that even a blow with a golf club, for example, would cause, at worst, only a crack and devacuation of a tube and not a violent implosion with the throwing of glass particles away from the picture tube.

Supplemental protection is added to the bulb to ensure that such a violent implosion could not occur. One approach to achieve this is the addition of a laminated curved glass section onto the faceplate of the tube, sealed with a thermoplastic resin. A second approach is the use of a metal band tensioned around the sidewall of the panel to provide a compressive force which in turn redistributes the stresses of the face so that in case of a mechanical failure no glass is thrown and the bulb typically will crack and go to air quietly rather than have any violent implosion. In one metal-band system, pieces of metal 0.5 mm thick are formed to the general contour of the faceplate sidewall and extend just around the edge to provide a lip at the external edges of the face of the tube. The pieces are normally secured to the glass sidewall by a resin glue and then held in place by a tensioned band. This band is normally pulled taut with a force of the order of 600 kg, and then secured to itself either by means of a metal crimp or by welding. A combination of this tension band and the glued metal pieces provides complete protection of the finished tube. Various modifications of this system have been used which include a one-piece metal shell about the faceplate end of the tube which is subsequently filled with a resin to completely fill

the area between the glass and the metal part. Another system uses a one-piece metal assembly which may be made of several welded sections and is slightly smaller in size than that of the glass panel. In this case, the metal assembly is heated to 300° or 400°C to expand it and while still hot slipped over the glass panel. As the metal cools it contracts around the panel and puts the glass under compression which provides a system similar to that of the tensioned metal strap previously described.

Various types of mounting lugs or ears are frequently attached to the metal pieces employed in the implosion prevention system to facilitate the mounting of the picture tube in the receiver cabinet.

It has long been the practice to add neutral absorbants in the panel glass to improve picture contrast by suppressing halation in the faceplate and ambient light reflection from the screen. Panel faceplates with as little as 42% transmission have been used for color tubes, but the use of the light-absorbing matrix permits much higher transmission, as will be described in Section 5.5.

Even with highly absorbing glass, front-surface reflectivity from the faceplate glass still exists and may deteriorate the video image as seen by the viewer. For example, the convex curvature of the outer tube face tends to accentuate the formation of reflected lamp images and the like that are superimposed on the picture. Remedies have been developed consisting of a coating or surface finish that smears the reflected image but has little effect on resolution of the video image.

5.3.10 Magnetic Shielding of Shadow-Mask Color Tubes

Magnetic shielding must be provided for shadow-mask color tubes to reduce the influence of magnetic fields on electron trajectories as the tube is scanned. In particular, the angle of incidence of the beam at every point on the mask must not change significantly from the design value, or the beam will move away from its intended landing position on the screen. The magnetic-field sensitivity extends to very small changes in the ambient field relative to the color tube such as those produced by rotation of the TV receiver in the earth's field.

Shield designs using soft magnetic materials have been developed for placing the shield either inside the tube or just outside the tube. Also, the low-carbon-steel shadow-mask is an important part of the shield system. Such materials, to be effective, must be thoroughly demagnetized (degaussed) in position. The degaussing may be done by subjecting the shield to the field from a coil energized by alternating current of progressively reduced amplitude from the power line. This procedure effectively reorients magnetic domains in the shield and tends to leave it magnetized so as to

nullify the field within the shield. The degaussing coil may be built into the receiver and the alternating current automatically reduced from a high value to zero every time the receiver is turned on. This insures against deterioration of color purity and white uniformity caused by changing magnetic field environments.

A better understanding of the effect of a magnetic field is attained by separating it into three orthogonal components. Since the vertical component of the earth's field remains relatively constant when the tube is used in the northern hemisphere, compensation for this component is most easily achieved. This may be done by taking into consideration the magnetic displacement of the beams in the lighthouse lens design. The z component, or the field component parallel to the tube's axis, causes the largest uncorrectable beam displacement and, with shielding, typically produces misregister in the order of 15–25 μm.

Effective shielding of a color tube depends not only on the magnetic properties of the shield and its geometry but also on its placement with respect to the beam path in the color tube. A knowledge of the sensitivity of the beam to magnetic fields as a function of distance along the path is helpful in determining the extent of the shield needed and where best to place the shield. Detailed analysis shows that maximum sensitivity of spot position results from fields at the shadow mask, decreasing linearly toward zero at both the deflection center and at the phosphor screen. Expressions have been given in Section 5.3.2 for the total spot displacement, when a tube is transferred from a field-free environment into a uniform magnetic field.

The coercive force of the magnetic shield should be as low as possible. For cold-rolled steel, this may be obtained by use of low-carbon material and suitable firing to further decarburize the material. In addition to the shield itself, the shadow mask makes a significant contribution to the total shielding of the tube. Cold-rolled steel 0.15 mm thick is commonly used for the mask material. The use of low-carbon materials or decarburization enhances the effectiveness of the shielding.

The shield may be either inside the tube envelope or placed on the outside. The usual practice in the United States is to use an external shield. In Europe, it is customary to use a push-through type of mounting of the picture tube in the receiver wherein the face and a portion of the sidewall of the tube is exposed in the front of the receiver. With this configuration an external magnetic shield which does not extend to the front of the picture tube is used. The shorter length of the shield reduces its effectiveness. In Europe therefore, particularly in the case of 110° tubes, it is the practice to place the magnetic shield inside the tube. This shield is usually made of

0.1–0.15-mm thick cold-rolled steel and is welded to the mask support frame assembly during the tube fabrication. It must be designed to fit the bulb envelope and be as close to the bulb wall as possible so that it will not provide a surface from which overscan electrons will be scattered back onto the screen.

Because of lower coupling to the external degaussing coil, an internal magnetic shield usually requires a higher amount of degaussing current than an external shield. Degaussing is normally expressed in terms of ampere turns, and typically for 110° internal shields, would be in the order of 1500 A turns. An external shield can be degaussed with half this value.

5.4 110° Systems

The obvious advantage of 110° systems over 90° systems is the shorter overall tube length obtained and, therefore, the improved compactness and cabinet styling that is possible in the receiver. For a 25V (626 mm) tube, this saving in overall length is about 100 mm. A second advantage of the 110° system is a shorter throw distance for the electron beam which results in a smaller focused-spot size. In most other aspects, the design of 110° systems becomes more complicated because of the following factors:

(1) Higher deflection power is required if other parameters of the system are kept constant.

(2) Electron-optical distortion of the beam triads and distortion due to obliquity factors in screen geometry become greater with an increase in deflection.

(3) An increased amplitude of dynamic convergence is needed, so the problems of achieving satisfactory convergence become more difficult.

(4) Electron beam deflection defocusing becomes greater.

One approach to mitigate the disadvantages of the 110° system has been to reduce the neck diameter so the deflection power and the dynamic convergence requirements do not greatly increase over the 90° system.

The first commercial 110° color system employed an 18V (457-mm) screen size (*67*). It utilized a 29-mm diam neck which reduced the deflection power and convergence requirements compared to that required in a 36-mm neck 90° system. The yoke and scaled-down version of the gun were very similar to that commonly employed in 90° systems. Even with the smaller gun size (see Fig. 5.27), good resolution was obtained because of the shorter throw distance. The shorter throw distance also aided in convergence.

In larger-size tubes, for example the 25V (626 mm), two different systems have been commercially employed. One system utilizes a 29-mm neck and the second a 36-mm neck. The gun employed with the 36-mm neck is similar to that used in the 90° system; the misconvergence and triad distortion were minimized by the use of a special circuit to provide a "current-difference waveform" to the two halves of the horizontal yoke windings.

The yoke itself was designed to give no astigmatism along the vertical and horizontal axes of the screen which means the equilateral shape of the beam triad will be maintained on axis. The size of the triad may be changed but not the shape when dynamic convergence is applied. With such a yoke, convergence at the corners of the raster cannot be obtained by the simple sum of horizontal and vertical dynamic convergence. To obtain corner convergence, the two halves of the horizontal windings are modulated with an equal, but opposite, current waveform at horizontal rate. The amplitude of this waveform is proportional to the product of the instantaneous values of the horizontal and vertical deflection. This modulation corrects corner astigmatism and produces corner convergence.

Another system, utilizing the smaller 29-mm neck, makes use of a precision toroidal yoke wherein control of the winding distribution can be precisely held by placement of the individual wires in accurate mechanical plastic combs at either end of the yoke. A typical yoke of this type, called *precision static toroid yoke* (*19*), is shown in Fig. 5.41. It has been possible with such a yoke to obtain triad distortions that are comparable to that commonly found in 90° yokes, and to obtain adequate convergence with a

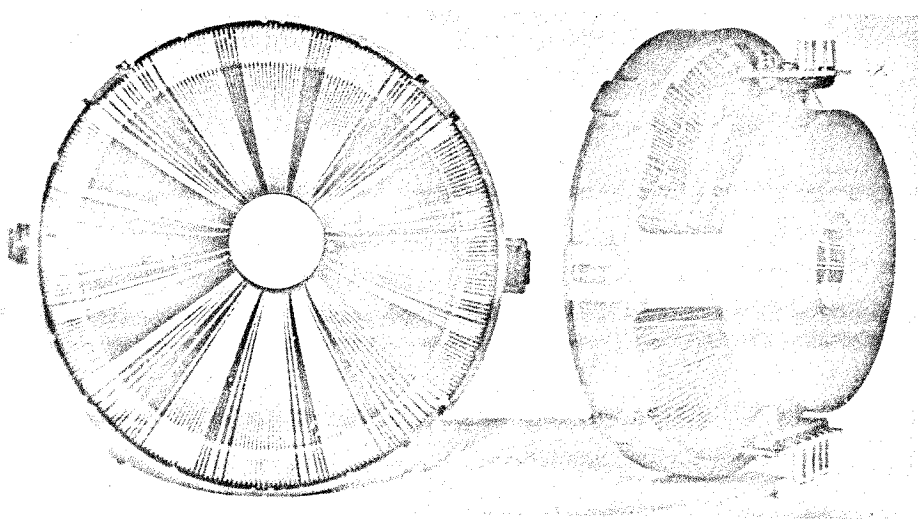

Fig. 5.41. Photograph of PST yoke.

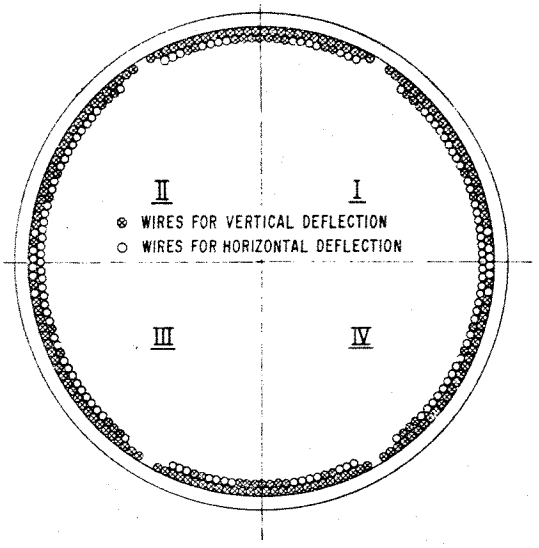

Fig. 5.42. PST winding distribution.

90° dynamic convergence system. This desirable yoke performance is in part due to the longer effective magnetic field of the toroidal yoke. The deflection field originates as the leakage flux from the two opposing sections of each of the vertical and horizontal deflection windings. The mechanical features of the toroidal yoke allow any desired intermixing of vertical or horizontal windings around the circular ferrite core. Figure 5.42 shows a typical winding distribution for a 110° toroidal yoke. Using the freedom to select winding distribution, an optimum design can be achieved for best convergence and for minimum triad distortion. Control of these characteristics is achieved by the accurate and repeatable mechanical placement of the windings.

The problems of obtaining and maintaining good register between phosphor dots and the electron beam spots increase with the higher deflection angle. Of special importance are problems of mechanical stability that will affect the spacing between the shadow mask and faceplate. After the screen is printed on the lighthouse, as described in Section 5.3.5, a change in spacing between the screen and shadow mask will affect register in proportion to the tangent of the half-deflection angle. For example, a change in this spacing by 0.1 mm near the diagonal corner of the screen will affect register on a 90° tube by 0.1 mm and on a 110° tube by 0.143 mm. This increase can be compensated for in the design of the lighthouse lens providing

the increase remains fixed at the new value. Any variation in this value from tube to tube must be accepted as a tolerance. The principal factors causing change in screen-to-mask spacing are the movements of the mask and the glass panel through thermal tube processing cycles. These movements tend to be random in nature except for the tendency of glass to compact or increase in density with thermal cycling and for the face panel to flatten when vacuum-loaded. Typically, a 25V (626-mm) panel will flatten about 0.15 mm under vacuum exhaust.

Other mechanical factors that have a greater effect on 110° than on 90° tubes include the thermal expansion of the mask. While the average steady-state expansion can be corrected completely by the bimetal mask mounting system described in Section 5.3.8, a transient expansion of the mask will cause a reduction in the mask-to-faceplate spacing when it is due to uneven heating or the heating of the mask before the frame temperature has risen. These transient temperature changes will cause more change in register with 110° deflection than with 90° deflection as previously discussed. One method of reducing the transient mask expansion problem has been to put a black, or high thermal-emissivity coating, on the back of the aluminized screen. This coating allows the panel to absorb radiant heat from the mask rather than reflect it as would be the case with a shiny aluminum coating.

The application of an implosion protection system to the panel may also affect register. Since most of these systems, as discussed in Section 5.3.9, place the skirt of the panel in compression, there is a tendency to make the faceplate bulge out slightly. Again, if the distortion is consistent from tube to tube, this effect may be compensated for in the design of the lighthouse optics.

5.5 Matrix-Screen Color Tube Systems

The matrix-screen concept for shadow-mask color picture tubes makes it possible to design the tube for greater brightness and/or greater contrast than is possible in a nonmatrix design (*68*). To understand the basis for the improvements, it may be instructive to review the major factors affecting brightness and contrast. Brightness is primarily determined by the anode voltage, anode current, screen efficiency, and transmission of the faceplate through which light from the phosphor must pass in getting to the viewer. An unwanted factor is ambient light reflected from the screen to the viewer. Its major effect is to degrade picture contrast by limiting the blackness of the black that can be obtained on the screen or to limit the black level in the picture. To counteract this effect, it has been customary

in black-and-white picture tubes, and for many years prior to the advent of matrix screens in color tubes, to use light-absorbing or "gray-glass" faceplates. The advantage of using a gray-glass faceplate is that part of the ambient room illumination which is reflected from the screen and gets to the viewer must pass through the gray glass twice. It is therefore attenuated twice while light originating from the phosphor that gets to the viewer is attentuated only once. The contrast ratio or brightness ratio of the high light to the black level in the picture is thus increased, but at the expense of picture brightness. Generally, the brightness loss is 50–60% in nonmatrix color tubes.

The basis for improvement of the nonmatrix design by incorporation of a matrix is the reduction of screen reflectivity for ambient illumination and at the same time removal of much of the attenuation used in the gray-glass faceplate. By so doing, the black-level degradation which results from ambient light falling on the screen is kept at a low level because the screen is less reflective while the picture is brighter because the picture light is attenuated less in the faceplate.

A reduction in screen reflectivity is possible because the area of the screen hit by the electron beam as the beam comes through the shadow mask is only 50–75% of the total screen area. The unbombarded area serves as tolerance for landing of the beam on the phosphor dot or line. Much of this area can be made nonreflective or converted to a black matrix surrounding the phosphor elements without reducing the light generated in the phosphor.

There are two approaches to designing a matrix for the shadow-mask tube, the difference in the two depending on how the tolerance for beam landing on the phosphor dots is handled. In the first approach, here designated positive-tolerance matrix, the matrix openings or phosphor dot diameters as defined by the matrix openings, are larger than the electron spots. It has an advantage in simplicity of manufacture, but its performance is limited in that only a relatively small black matrix area can be added before the tube screen tolerance is reduced beyond an acceptable level, although screen tolerance requirements may be reduced by improved manufacturing techniques and controls or the acceptance of less rigid performance requirements for color field purity and uniformity of the white field. In the second approach, here designated negative-tolerance matrix, the matrix openings are smaller than the electron spots. In this design it is desirable to both enlarge the mask apertures to achieve larger electron spots and reduce the matrix openings. The inverted phosphor dot-electron spot size relation is responsible for the negative-tolerance designation. Figure 5.43 shows typical nonmatrix and matrix designs to illustrate the geometric relationships that have been described. For simplicity, the screen and electron spot

systems are assumed to be perfectly nested and the electron spots have sharply defined edges without umbra-penumbra gradations that exist in practice.

The simplified Fig. 5.43 also can be used to describe the concept of screen

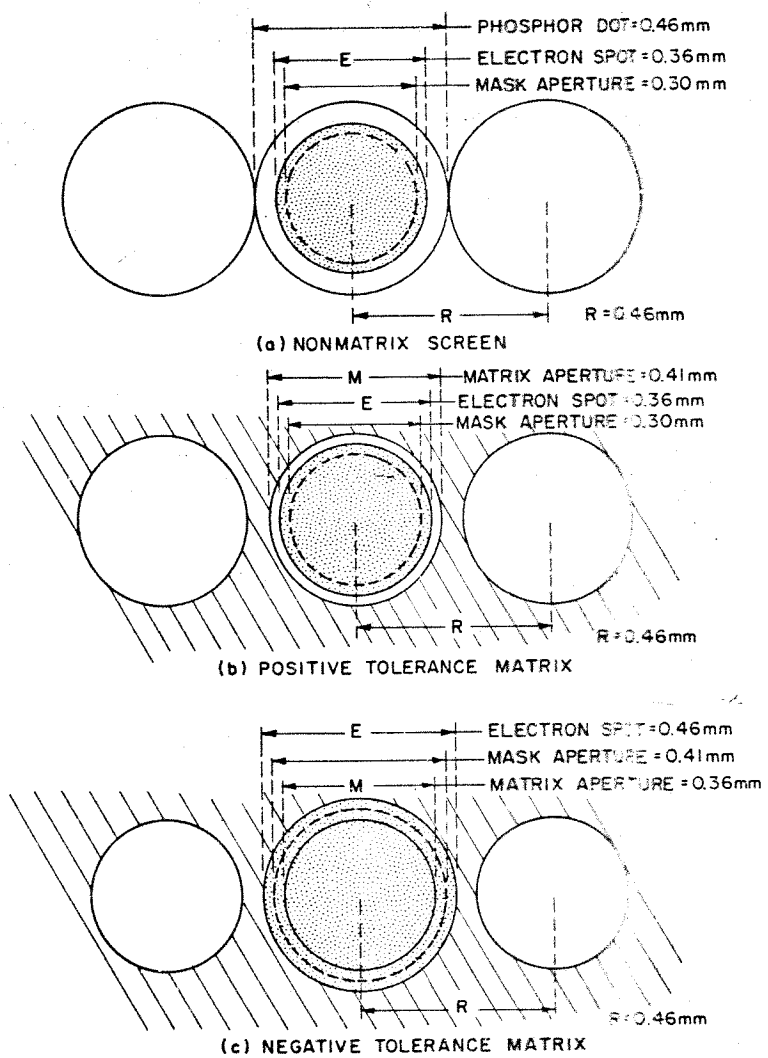

Fig. 5.43. Illustration of (a) nonmatrix, (b) positive-matrix, and (c) negative-matrix designs. The illuminated phosphor-dot areas are the same in each case. R is the distance between phosphor dots.

tolerance for each type of screen. In the nonmatrix case (Fig. 5.43a), the electron spot is smaller than the phosphor dot and will produce the same amount of light as long as it lands within the phosphor dot. The tolerance for the spot beginning to leave the dot, or leaving tolerance, is defined as the total maximum distance the electron spot can move without altering the amount of light emitted from its phosphor dot. For the nonmatrix case the leaving tolerance is then just the difference in diameter of the phosphor dot and electron spot or 0.1 mm as shown in Fig. 5.43a. For the positive matrix, where the phosphor dot diameter is the matrix aperture diameter, the leaving tolerance is 0.05 mm as in Fig. 5.43b. The same definition also applies for determining leaving tolerance in the negative tolerance case, but in this instance the electron spot is larger than the matrix aperture. The sample negative tolerance screen of Fig. 5.43c has a leaving tolerance of 0.1 mm.

If in each of the three screen types the leaving tolerance is exceeded in an operating tube for some reason, the actual hue change produced will depend on whether adjacent phosphor areas are now illuminated by the beam spots that have moved. A second kind of tolerance has been specified to cover this contingency. It is called clipping tolerance. Clipping tolerance is the total distance the electron spot can move before it reaches an adjacent area of visible phosphor. Clipping tolerance is then

$$T_C = 2R - M - E$$

where R is the spacing between matrix apertures (phosphor dots in nonmatrix screen), M is the matrix aperture diameter (phosphor dot diameter in nonmatrix screen), and E is the electron spot diameter. By inspection of Fig. 5.43, the clipping tolerances are:

0.1 mm	nonmatrix
0.15 mm	positive tolerance
0.1 mm	negative tolerance

In the above examples, it is assumed that the beam spots and phosphor dots are in perfect register.

Each of the systems are dependent on leaving and clipping tolerances in ways that play a distinctive role in tube operation. For example, in the nonmatrix screen where leaving and clipping tolerances are equal for tangent phosphor dots, white uniformity is seldom a problem if the screen has good color-field purity. That is, color-field purity requires only that the electron spots fall entirely within the phosphor dots or that leaving tolerance is not exceeded. White uniformity requires in addition that the relative current to the dots of each triad be equal over the screen. Since in the absence of a

matrix in a nonmatrix tube the current for all three beam spots in a given triad is limited by the same aperture, this requirement is met automatically.

In the positive tolerance screen the same situation holds as for the nonmatrix screen, although leaving and clipping tolerance are no longer equal except in the limit when the matrix apertures are tangent. If the matrix openings are smaller than required for tangency, then it is possible for an electron spot to begin leaving an opening without striking an adjacent phosphor dot. If this happens color purity will not be affected as such, but a reduction in light generated in the dot will take place. Should this happen in one phosphor dot of the triad, then white uniformity is degraded. Color purity is therefore easier to maintain than white uniformity.

The negative tolerance situation is much different. Because the electron beam spots completely cover the matrix openings, white uniformity depends on having throughout the screen the same relative transmission of the openings in each matrix triad. In effect there is a potential for building into the screen a nonuniformity in white that cannot be corrected by operating controls in the receiver. More will be said about this in the next section under Matrix Screen Construction. With regard to leaving and clipping tolerances in the negative-tolerance system, it is possible to favor either one over the other by the choice of mask and matrix openings.

In general the discussion has assumed well-nested, equilateral phosphor-dot triads and beam-spot triads. Distortions in the beam-spot triads, which may occur particularly near the edge of the picture area, will require that somewhat smaller phosphor dots be used to prevent dot overlap. The situation is further aggravated when phosphor dots cannot be printed in precisely the desired place because of lighthouse lens limitations. As in the nonmatrix system, matrix screen tubes make use of masks with aperture sizes graded to smaller diameter at the edge than in the center to obtain increased tolerance at the edge.

The negative-tolerance matrix tube using a faceplate transmission of about 85% had evolved by 1973 as an attractive system. A transmission of 85% is the highest value it is practical to get without objectionable tint and therefore represents a design for maximum light output. Other details of the design such as the choice of mask transmission and the percentage of the screen surface covered by the black matrix are related to trading brightness for screen tolerances which affect color purity and white uniformity. An adequate discussion of these choices, dictated largely by manufacturing considerations, is beyond the scope of this volume, but an illustration of the magnitude of performance changes that can be achieved with a matrix design over a nonmatrix design is given in Fig. 5.44. Typical matrix and nonmatrix tubes are here assumed to be operating under significant

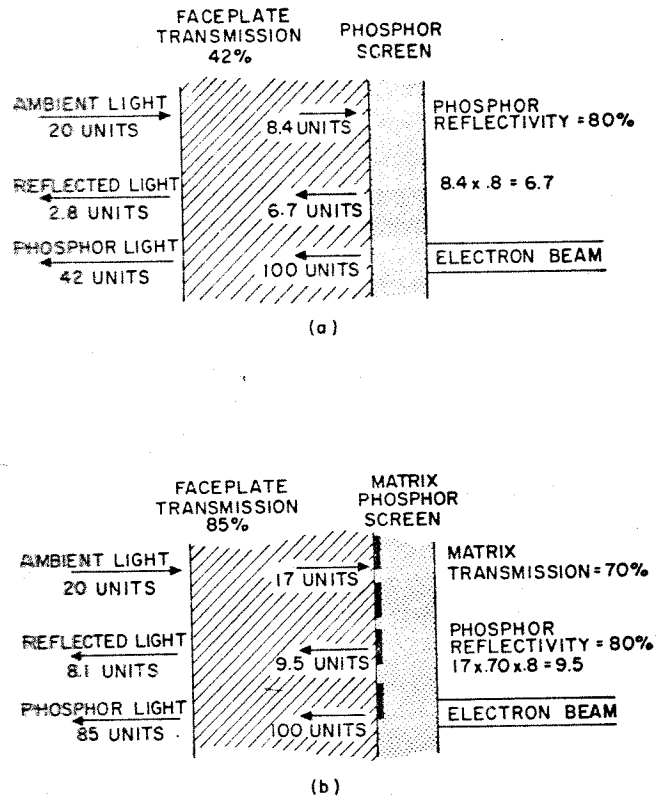

Fig. 5.44. Relative matrix screen brightness gain over nonmatrix screen when the same area of phosphor is exposed to the electron beam in the two systems. (a) Nonmatrix screen: brightness, 42 + 2.8 = 44.8 units; contrast, 44.8/2.8 = 16; black level, 2.8 units. (b) Matrix screen: brightness, 85 + 8.1 = 93.1 units; contrast, 93.1/8.1 = 11.5; black level, 8.1 units. The brightness gain is 93.1/44.8 = 2.1. Both the contrast and black level are less favorable.

ambient light. The relative brightness, contrast, and black level are obtained under the reasonable assumption that the matrix tube phosphor dot as defined by the matrix opening is the same area as the electron spot on the phosphor dot in the nonmatrix tube. That is, assume the same amount of light is generated by the electron beam in the two systems.

Several observations relating to nonmatrix, positive matrix, and negative matrix color tube systems are as follows:

1. In a positive-tolerance matrix tube and in a nonmatrix tube, the largest mask aperture permitted by tolerance considerations is desirable.

In the case of the matrix tube, this corresponds to a large matrix opening and a small amount of black.

2. In a negative-tolerance tube, both brightness and contrast increase as the matrix openings increase, but black level degrades. Thus, the largest matrix opening permitted by tolerance considerations is desirable for best brightness-contrast performance. This corresponds to the least amount of black material.

3. In positive-tolerance tubes, the clipping tolerance is greater than or equal to the leaving tolerance while in negative-tolerance tubes, the clipping tolerance may be either larger or smaller than the leaving tolerance.

4. For the same leaving and clipping tolerance, the mask transmission* of positive-tolerance designs is equal to the effective matrix transmission of negative-tolerance designs. Thus, for the same glass transmission, there is little difference in brightness between the two types. There is, however, a significant contrast advantage in the negative-tolerance type which can be traded for a brightness advantage by increasing the glass transmission.

5. In negative-tolerance tubes, localized variations in the ratios of the red-, green-, and blue-matrix openings will cause a change of white balance. Thus, control of the relative matrix openings is an important factor in the production of a negative-tolerance tube.

Matrix Screen Construction

The processes used in making color screens for shadow-mask tubes have already been described in Section 5.3.5. Matrix screen construction differs primarily by the need to add procedures for printing the matrix.

As indicated in the earlier discussion, the basic screen printing technique is exposure of a light-sensitive colloid, usually PVA, which may contain phosphor as a pigment. The exposed area becomes insoluble and remains after development. On the other hand, matrix printing requires a process that has the reverse polarity because the matrix openings should be clear with the surrounding area black. Several processes have been developed that can produce this result. However, the most common one (*69*) is a reverse printing process that uses PVA photosensitive material which hardens on exposure to ultraviolet light. In this process, clear unpigmented PVA is exposed in the lighthouse from all three color-center positions. After development, the surface contains a system of clear dots in the positions later to be openings in the matrix. Next, a water suspension of graphite is slurried on the surface and dried. An aqueous solution of H_2O_2 is then used to develop the matrix. The H_2O_2 disintegrates the PVA dots and dislodges the

* In the limit of zero electron beam diameter in the deflection plane, or the absence of a penumbra.

overlying black layer while leaving undisturbed the graphite that is in direct contact with the glass. After the matrix is formed, phosphor dots are printed by the processes described for nonmatrix tubes.

Printing negative-tolerance matrix screens poses a problem not encountered in nonmatrix and positive-tolerance matrix screens, because the mask apertures in negative-tolerance tubes are larger than the matrix openings desired. In using the matrix reverse printing process, it is therefore necessary to print PVA dots that are smaller than the mask apertures. Three possibilities exist. First, the mask apertures may initially be made small for printing purposes, and then after the matrix and screen are printed, the mask is postetched to enlarge the apertures to the size required in the operating tube (*70, 71*). Second, the resist coating containing small openings that is applied to the mask when etching the mask apertures may be left on after the etching is completed and serve as a printing mask for the large apertures (*72*), or the mask apertures may be initially large and then temporarily restricted in size by a coating applied to the mask. The coating is removed after the printing operations are completed. Third, an appropriately chosen printing light-source size aided by light diffraction at the apertures may be used with precise exposure control to "print down" and obtain dots smaller than the mask apertures.

The first method is the basis of a commercial process. In the second method, where the etch resist is left on, heat treatment of masks after etching is not possible. Hence the mask must be etched after forming the mask to a spherical curvature, which severely limits the method. Coating methods are the subject of many patents which describe techniques such as plating, spraying, cataphoretic deposition, etc., but none has been used commercially. The third method, print down, plays a part in printing even nonmatrix phosphor screens; properly used, it becomes very important as the basis for an attractive matrix printing process that does not require alteration of the mask for printing the matrix and screen. That is, the size of the printing light source and diffraction of light at the aperture edge influence the light distribution in the dot projected on the screen in the printing process. The intensity profile of this distribution relative to the mask aperture dimension can, under certain conditions, become favorable for printing PVA dots smaller than the apertures. For example, if the light intensity distribution at the screen plane from an aperture falls off with sufficient gradient at the desired dot diameter, then dots of this diameter may be printed by precise control of exposure. Fortunately, clear or unpigmented PVA photoresist may be used so that light scattering is a minimum during exposure. The basic simplicity of printdown makes it important to review the optical principles involved so that full advantage may be taken of this method of matrix printing.

Assume a monochromatic point light source of wavelength λ is produced, for example, by focusing a laser beam with a microscope objective of large numerical aperture. If this source is placed at the deflection center, a distance p from the mask aperture of diameter B, the intensity distribution $I(r)$ on the screen, a distance q from the mask, is given by

$$\frac{I(r)}{I_0} = F(\rho, y) \qquad \text{with} \qquad \rho = \frac{2rp}{B(p+q)}, \quad y = \frac{\pi(p+q)B^2}{2pq\lambda} \tag{5.86}$$

Here I_0 is the intensity in the absence of diffraction within the geometrically projected light spot of radius $B(p+q)/(2p)$ and F is a universal function of the relative radial distance ρ and the parameter y. Figure 5.45 shows the function $F(\rho, 25)$, the parameter $y = 25$ corresponding, for example, to

$$B = 0.3 \text{ mm}, \qquad q = 15 \text{ mm}, \qquad p = 245.9 \text{ mm}, \qquad \lambda = 4 \times 10^{-4} \text{ mm}$$

These geometric parameters might be realized in a large-screen, large deflection-angle tube with a matrix screen. Since $25 \cong 8\pi$ and, quite generally,

$$I(0)/I_0 = 4 \sin^2(y/4) \tag{5.87}$$

the intensity is seen to drop to zero at the center of the light spot. On the other hand, for $y = 10\pi = 31.42$, realized by reducing, in the preceding example, the wavelength to 3.18×10^{-4} mm or q to 11.79 mm we would obtain the dotted curve for the distribution near the spot center, with $I(0)/I_0 = 4$.

The distribution near the center of the light spot is thus highly wavelength-and-q-dependent. At the geometric shadow edge it is much less so. For $B/2 \gg (\lambda q)^{1/2}$, we must expect behavior similar to that at the shadow edge of a straight edge, i.e., $I/I_0 \cong 0.25$ at the shadow edge ascending to a maximum of the order of $I/I_0 = 1.37$ a distance approximately equal to $(\lambda q)^{1/2}$ from the edge toward the center of the light spot and decreasing monotonically from the edge into the shadow region. For a point source with a wide spectral distribution we might thus expect the distribution in the interior of the spot to be smoothed out, retaining the reduction of the intensity at the geometric edge to 1/4 the mean intensity in the spot and an intensity variation characteristic of a median wavelength near the geometric edge. If, in addition, the light source is relatively large, i.e., has a diameter of the order of $(p/q)B$, the distribution is both broadened and changed from a flat-topped to a more nearly conical shape.

The sources most commonly used for printing shadow-mask screens utilize high pressure mercury arcs, with spectral distributions similar to that shown in Fig. 5.46 (*73*). The spectral response of the photoresist is such that only the narrow spectral distributions centered about 365 nm and

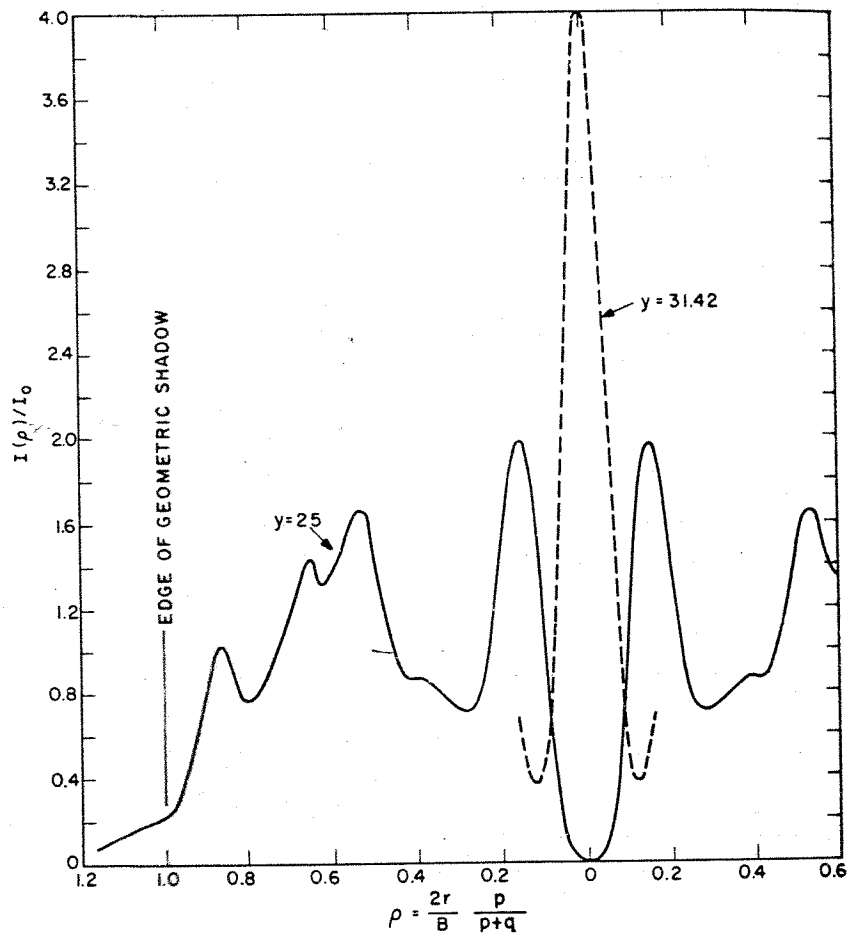

Fig. 5.45. Intensity distribution in light spot projected on screen by monochromatic point source at deflection center through mask aperture.

400 nm are effective (Fig. 5.47) (*74*). It is thus not surprising that the intensity distribution at the screen plane of light that has passed through an aperture in the mask should exhibit a very striking intensity variation when produced by a source with diameter much less than $(p/q)B$ and measured with a sensor with the spectral response of the photoresist. The result of such a measurement is shown in Fig. 5.48.* As the source diameter

* Measured by P. Kuznetsoff and J. Mirsch at the David Sarnoff Research Center, Princeton, New Jersey.

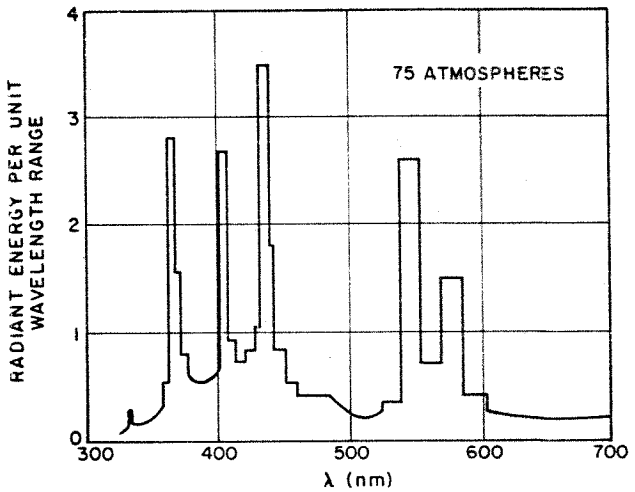

Fig. 5.46. Spectral distribution of emission from high-pressure mercury arc (*73*).

D_c is increased to the point that

$$[q/(p+q)]D_c = 0.38B \tag{5.88}$$

the effective distribution is found to assume a conical shape, leaving only a slight dip at the center (Fig. 5.49).*

As previously indicated, the intensity distribution in the light spot is of particular importance in matrix printing. The accuracy with which the

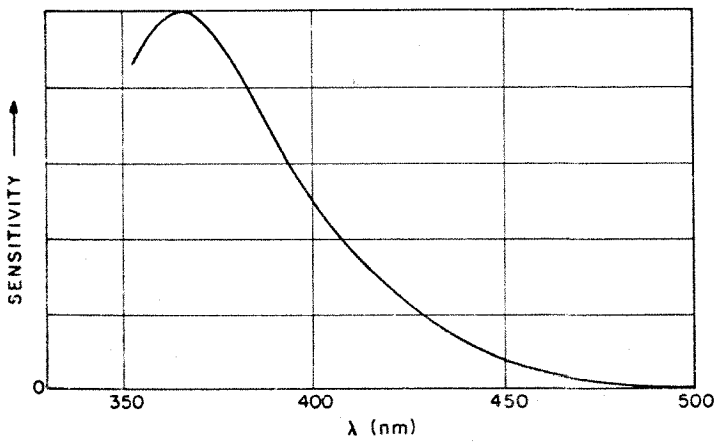

Fig. 5.47. Spectral sensitivity characteristic of hardening of polyvinyl-alcohol solution sensitized with dichromate (*74*).

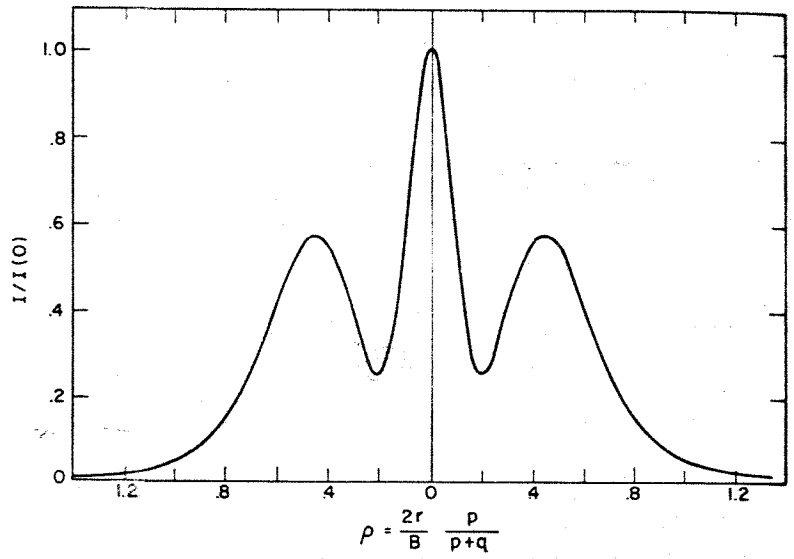

Fig. 5.48. Effective intensity distribution in spot projected by 0.38 mm source.

printed dot area can be realized is proportional to the quantity

$$\frac{\text{fractional error in exposure } E}{\text{fractional error in dot area } \pi D^2/4} = \frac{D}{2E}\frac{dE}{dD} = \frac{r}{2I}\left(-\frac{dI}{dr}\right) \qquad (5.89)$$

This quantity obviously has a large value if the critical exposure which marks the boundary of the developed dot corresponds to a large value of the diameter $D = 2r$ and a small value of I, close to the edge of the intensity distribution, where the slope $-dI/dr$ is still large.

In summary, dots larger than mask apertures are readily printed, but in printing a negative-tolerance matrix by the reverse-printing process described above, the PVA dot size should be smaller than the mask aperture size. We can obtain the smaller dot size by employing a printing light source that gives a more or less conical light intensity distribution back of each aperture at the screen plane and reducing the exposure to such an extent that the critical exposure occurs at the much smaller dot diameter desired, and at a correspondingly much greater value of $I(r)/I_0$. The relative printing accuracy given by Eq. (5.89) is now much smaller or, in other words, the required uniformity in exposure and photoresist sensitivity much greater.

5.6 In-Line Gun Systems

The advantage of an in-line configuration of guns in a shadow-mask display is the potential for simplified convergence. With spots from coplanar beams initially converged at the center, and the beams well aligned with the yoke, all that should be required to maintain convergence during scan is to move the outside beam spots along the line of centers to the center spot. Moreover, the basic delta-gun shadow-mask tube can be designed to use an in-line gun with essentially no geometric modification of the shadow mask or phosphor dot screen pattern. As shown in Fig. 5.50, when the in-line gun array is horizontal, the phosphor dot triads become three dots in a horizontal line, and the triads nest together to form the same overall phosphor dot pattern as in the delta system. An individual mask aperture is aligned with the center phosphor dot of the line triad in contrast to the delta-gun system where the aperture is aligned with the center of the triangle of phosphor dots forming the triad.

However, distortion of the electron-spot triads, as described in Section 5.3.2 and illustrated in Fig. 5.13 for the delta system, is also present in the in-line system because of the spherical shape of the mask and screen. The distortion is a foreshortening of the triads in the radial direction; and, in the case of line triads, results in an effective rotation or tilt of the line

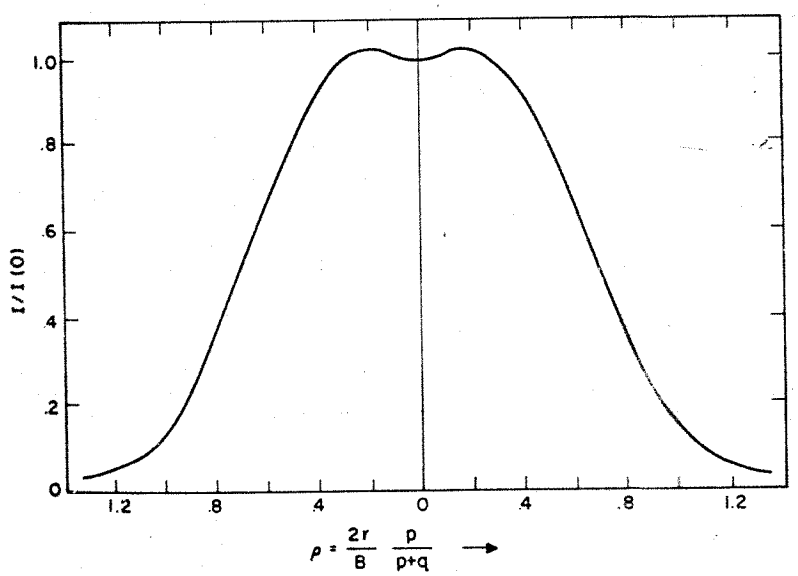

Fig. 5.49. Effective intensity distribution in spot projected by 2.0 mm source.

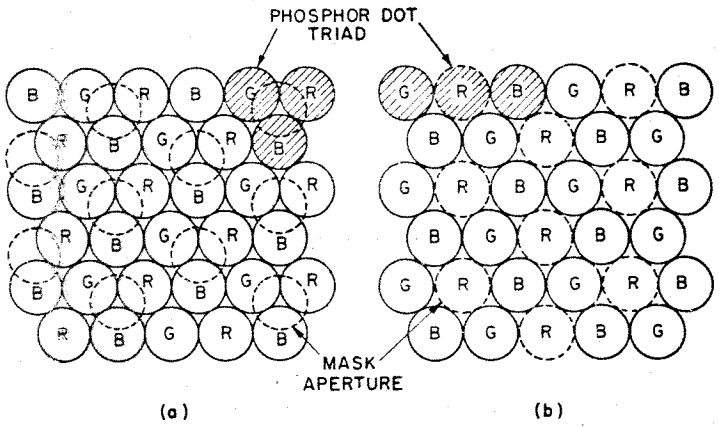

Fig. 5.50. Nesting of (a) delta gun-mask and (b) in-line gun-mask phosphor-dot triads, and the geometric arrangement of the triads with respect to mask apertures.

triads in the corners shown in Fig. 5.51. The geometric or obliquity distortion causes sufficient tilt to seriously reduce color purity tolerance, unless corrective measures are taken. One such measure is to distort the mask aperture array (*75*) so that rows of apertures tend to follow the direction of triad tilt. Another is to design astigmatism into the yoke to produce a triad tilt in the opposite direction to nullify the obliquity tilt, but this method would require corner convergence waveforms.

An entirely different approach that largely avoids this screen tolerance problem, while retaining simplified convergence, is to change the round mask apertures into vertical slits and use a phosphor screen in the form of continuous vertical stripes. Tilt of the electron spot-line triads can then be tolerated without causing color impurity if proper nesting of the electron spots on the screen surface is obtained by the appropriate choice of mask-to-screen distance. Screen printing is made easier because a lighthouse lens can now be designed to print phosphor lines in exact horizontal register with the electron-beam pattern, as discussed in Section 5.3.3. However, in practical development of simplified convergence for in-line systems employing round apertures as well as slit apertures in the mask, there are a number of important considerations which will now be discussed.

5.6.1 Deflection and Convergence of In-Line Gun Color Tubes

In discussing the convergence errors that take place during magnetic deflection, it is convenient to consider deflection defocusing of a hypothetical, large composite beam of circular cross section that, when undeflected, is focused to a point at the center of the screen. Three of its rays

represent the central ray of each of three individual beams. In the delta configurations, these rays lie on the surface of the large composite beams, separated by 120°; in the in-line configuration, they are the two external rays on the horizontal diameter and the central ray.

The ideal deflection yoke for in-line systems would cause no defocusing of the principal rays of the composite beam in its horizontal dimension as the composite beam is deflected. It would, however, cause deflection defocusing in the vertical dimension, to the point where the composite beam becomes distorted with deflection into a vertical line; but the rays of the composite beam, representing the central rays of the in-line beams, would still be converged as illustrated in Fig. 5.52. Such a yoke is designated a vertical line-focus yoke and ideally would exhibit vertical line focus at all points on the screen.

The design of a practical vertical line-focus yoke has to be carefully tailored to achieve a prescribed magnitude of astigmatism along the horizontal and vertical axes (slight over or under convergence), no anisotropic astigmatism (spot rotation in the corners), and no coma (raster-size mismatch on axes). Such a vertical line-focus yoke would deflect three horizontal in-line beams to all points of the screen with minimum misconvergence, provided the beams are initially converged at the center of the screen and properly aligned with the yoke. In the delta-gun system, no similar drastic simplification is possible. This is due to the fact that yoke design can eliminate deflection defocusing in only one dimension (horizontal

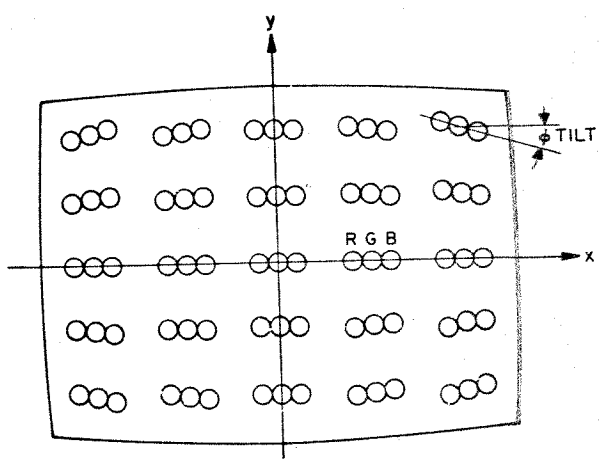

Fig. 5.51. Distortion of electron-spot triads at the screen when using an in-line gun and a spherical mask and faceplate.

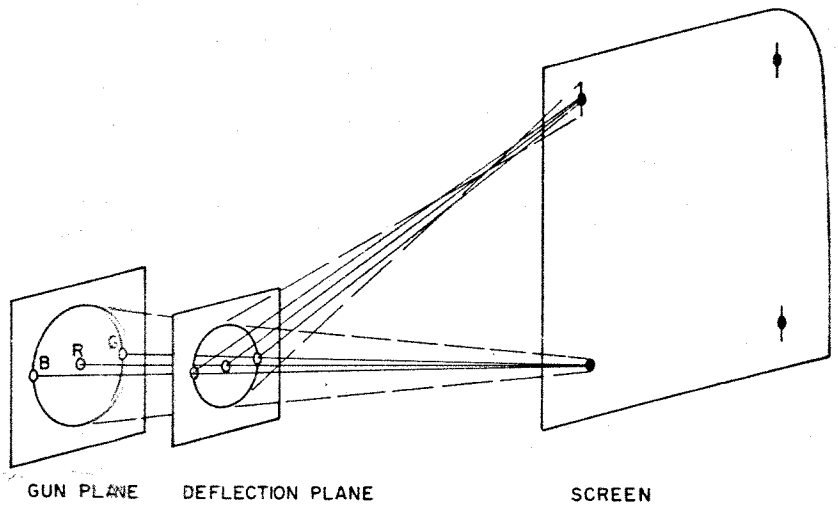

Fig. 5.52. Convergence characteristic of a line-focus deflection yoke.

or vertical) of the composite beam, but not in both. In the delta configuration, the three beams effectively span both dimensions of the composite beam. Yoke design can eliminate either misconvergence between horizontal lines with a horizontal line-focus yoke or misconvergence between vertical lines with a vertical line focus yoke, but not both together.

Display systems using horizontal in-line configuration of the three beams in shadow-mask (or grill mask) tubes have achieved simplified convergence in comparison with the delta-gun system. Two distinct 90° systems have been realized. In one case (*76*), the yoke exhibits essentially vertical line focus along the axes of the screen, but has horizontal and vertical coma. Line focus along the axes eliminates misconvergence between the two offset beams; coma causes a mismatch in the size of the rasters scanned by these two offset beams relative to the central-beam raster. In a commercial realization of this design (*23*), the raster-size mismatch is corrected by simple dynamic convergence waveforms (sawtooth at the horizontal and vertical scanning frequencies) applied to a simplified convergence assembly. The latter consists of four convergence exciters that act on the offset beams through two sets of internal pole pieces in the picture tube neck to produce horizontal and vertical convergence motions.

In another case (*77*), the yoke exhibits essentially vertical line focus along the vertical axis of the screen, but insufficient negative astigmatism (noticeable overconvergence) with substantial coma along the horizontal

axis. Here two magnetic exciters, driven by horizontal-frequency sawtooth and parabola currents that are controlled by one adjustment, act on the offset beams without internal pole pieces to produce the horizontal convergence motions required along the horizontal axis. In addition, two beam-alignment coils generating axial fields are driven by preset horizontal- and vertical-frequency sawtooth to provide vertical convergence motions of the offset beams along both axes of the screen for alignment correction.

A 114° version of this system was announced in 1973 (*66*). Here the yoke is free of coma and almost anastigmatic along both axes of the screen (substantial overconvergence along the axes). This system also uses two magnetic exciters, driven by horizontal- and vertical-frequency parabola and sawtooth currents that are controlled by two adjustments to produce the required horizontal convergence motions of the offset beams along both axes of the screen. In addition, two axial-field generating beam-alignment coils are driven by horizontal-frequency parabola and vertical-frequency sawtooth to provide vertical convergence motions of the offset beams for correction of beam/yoke-field misalignments.

The potential for simplification of convergence inherent in the in-line gun system has been fully realized in the *precision in-line* system (*25*). This system consists of (1) a shadow-mask picture tube including a unitized close-spaced horizontal in-line gun, (2) a toroid deflection yoke that exhibits effectively vertical line focus over the whole screen, (3) a means for centering the yoke on the picture tube to properly align the three beams in the yoke, and (4) an external static multipole low-permeability center convergence device. The absence of internal magnetic structures (except for small raster-size matching elements) permits achievement of optimum convergence by positioning the yoke in relation to the picture tube neck. The result is an inherently self-converging in-line shadow-mask display system that achieves convergence without the use of any dynamic convergence means (circuits, exciters, pole pieces).

5.6.2 In-Line Mask Construction Features

Two forms of masks have been developed especially for in-line gun tubes. In one, the mask consists of vertical strips formed by etching slit openings from top to bottom in a thin piece of metal (*24*). Higher transmission can be used with this type of aperture mask than a round-hole mask (approximately 19% vs. 16%), but the absence of cross ties restricts it to a flat or cylindrical shape and requires that it be mounted under tension on a relatively massive frame. In the cylindrical case, one or more fine wires under moderate tension may be placed on the convex surface of the mask to suppress vibration of the strips. Because of its shape, the aperture grill is used

with a cylindrically curved faceplate in contrast to the usual spherical curvature of a dot-type shadow-mask tube face.

The second type of mask, also made by etching thin metal, has vertical slits (*25*) separated by narrow horizontal webs, as shown in Fig. 3.1, that make it strong enough to be formed into a spherical shape; it provides the same transmission as the round-hole aperture mask. It is resistant to damage from mechanical and thermal loads because of its cross webs and can be used with the conventional spherical faceplate.

the condition for sharp focus for the mask with round apertures:

$$V_s/V_m = 9 \tag{6.6}$$

and for the mask with slit apertures:

$$V_s/V_m = 4 \tag{6.7}$$

If we take into consideration the fact that we image a source in the deflection plane, a finite distance p from the mask, onto the screen, we must replace $1/f$ in Eq. (6.5) by $(1/f - 1/p)$ and find, for the mask with the round apertures,

$$V_s/V_m \cong 9[1 + (2q/3p)] \cong 9(1 + \tfrac{4}{3}M)$$
$$M \cong (2q/p)[(V_s/V_m)^{1/2} + 1]^{-1} \cong q/2p \tag{6.8}$$

and for the slit mask,

$$V_s/V_m \cong 4[1 + (2q/3p)] \cong 4(1 + M), \qquad M \cong 2q/3p \tag{6.9}$$

M is here the (absolute value of the) magnification with which the individual lenslet projects the source onto the screen. Since this magnification is of the order of $\frac{1}{20}$, the correction of Eqs. (6.6) and (6.7) is minor.

Equations (6.6) and (6.7) tell us that if we just maintain the proper voltage ratio between mask and screen, the beam cross section in the deflection plane will be sharply imaged on the screen, irrespective of the mask-to-screen separation q. Moreover, a careful examination indicates that the focusing properties of the mask apertures remain essentially unaltered when the isolated aperture is replaced by an array of similar apertures formed by electrode elements which are narrow compared with the aperture diameter. In particular, a slit mask may be formed by a sequence of parallel wires with diameters $\frac{1}{10}$ of their center-to-center spacing; such a slit mask, in this instance with 90% transmission, is called a focus grill.

6.2 Three-Beam Focus-Grill Tube

The focus-mask principle, in the form of the focus-grill tube, was proposed in a patent awarded to Werner Flechsig (*79*) in 1941. A one-gun version, in which color selection is achieved by local deflection of the beam by electric fields between grill wires in a manner described by A. C. Schroeder (*80*), has become widely known as the "Lawrence tube," after the physicist E. O. Lawrence, who developed it in cooperation with Chromatic Television Laboratories, Inc. (*81*). One-gun focus-grill tubes, under

the trade names "Chromatron" and "Colornetron" have been produced commercially in Japan in limited numbers, by Sony Corporation and Kobe Kogyo Corporation, respectively. Their special features will be indicated in a later paragraph.

Three-gun focus-grill tubes have not attained large-scale commercial production. Their properties, and the special problems involved in their manufacture have, however, been investigated in considerable detail in industrial laboratories.

Focus-grill tubes quite generally employ line screens and in-line guns. With in-line guns, unlike delta guns, the lines traced by the two outer guns are symmetric with respect to the line traced by the central gun, so that nesting can be achieved simply by an appropriate variation of the mask-to-screen distance q over the screen surface. If, as usual, the phosphor line pattern is vertical, the variation of the horizontal component of the earth's magnetic field with change in orientation of the set has, furthermore, no effect on color purity—an advantage of line screens already noted in the discussion of shadow-mask tubes.

Early focus-grill tubes, like early shadow-mask tubes, were constructed with plane grills and plane screens, mounted within an evacuated envelope (*10*). The screens were generally printed by silk-screen techniques from masters prepared by electron exposure. The red, green, and blue phosphor line patterns were printed in succession, shifting the master by a phosphor line width between printings.

Later focus-grill tubes were prepared with the screen deposited directly on a curved faceplate (*11, 82*). Under these circumstances a lighthouse technique becomes appropriate (*83*). Again, an optical master has to be prepared for the screen exposure since the gaps between wires are much too wide to permit shadow projection.*

The light source may be placed at a distance yielding the same average grill pattern magnification on the screen as that effected by the electron beams and a correcting lens employed to assure that the printing light beams (projected on a plane normal to the grill wires) are incident on the screen at an angle equal to the mean inclination of the corresponding electron paths between grill and screen. Under these circumstances variations in the q value for different screens prepared with the same lighthouse (including correction lens) do not lead to registration errors (Fig. 6.2). As has already been noted, continuous-surface correction lenses for first-order printing can yield full correction of registration errors in line-screen

* It is interesting to note that Flechsig, in his original patent application, suggested thickening the grill wires with gelatin to permit screen deposition by a projection technique, the gelatin being washed off after screen preparation.

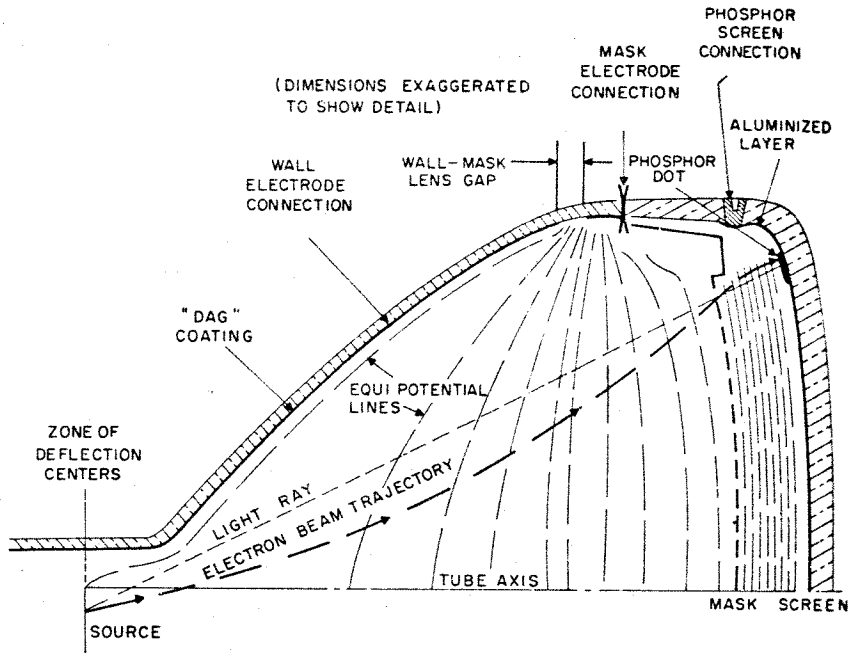

Fig. 6.7. Schematic representation of field distribution and structure of "unipotential mask-focusing Colortron" (CBS-Hytron).

In the CBS-Hytron tube the mask transmission was increased to 30%. With the aluminum thickness increased to reduce the effect of the back-scattered electrons, the residual brightness gain (over a shadow-mask tube with mask transmission 0.12) was found to be 2. The impact of secondary electrons from the mask was minimized by tapering the apertures in the relatively thick (1.3 mm) mask, reducing the diameter to a minimum on the gun side. The structure and the field distribution of the tube are indicated in Fig. 6.7.

6.5 Single-Beam Focus-Grill Tubes

Structurally, single-beam focus-grill tubes differ from three-beam focus-grill tubes in just three respects:

(1) The gun generates a single beam.

(2) Alternate wires of the focus grill are connected to two different electrodes; these are commonly joined by an internal resonating coil.

(3) The color sequence of the phosphor lines is, for example,

RGRBRGRB, with the green and blue phosphor stripes centered behind alternating grill wires, rather than RGBRGB, with the wire positions corresponding to the boundaries between successive triads.

The color selection voltage W is applied between the two sets of grill wires. For a flat grill and screen, and with the grill at the same potential as the gun anode, we can deduce the relationship between beam displacement Δx normal to the grill wires and the voltage W, for any direction of incidence (θ, ϕ) of the electron beam, in the manner used for deriving the condition for sharp focus. If E_x is the transverse field component resulting from the application of the potential difference W between the wires, the resulting change Δv_x in the x component of the velocity is given by

$$\Delta v_x = -(e/m) \int E_x \, dt$$

$$= -(e/mv)[(1 + \tan^2\theta \cos^2\phi)^{1/2}(1 - \sin^2\theta \sin^2\phi)^{1/2}]^{-1} \int E_n \, ds \tag{6.20}$$

Here E_n is the field component normal to the path projected on a plane normal to the grill wires and the integral over s is an integral over this projected path. The second root is the cosine of the projection angle, the first root is the secant of the angle between the projected path and the tube axis. v is the total velocity $(2eV_m/m)^{1/2}$. Application of Gauss' theorem to a slab of unit height bounded by planes parallel to the wires and passing through paths traversing the centers of adjoining spaces between wires in identical directions leads to (Fig. 6.8):

$$\int E_n \, ds = \frac{Q}{2\epsilon} = \frac{CW}{2\epsilon} \quad \text{with} \quad C = -\frac{\pi\epsilon}{\ln(\pi D/4d)} \tag{6.21}$$

Here Q is the charge and C the capacitance per unit length of wire. ϵ is the dielectric constant (of vacuum), D the grill-wire diameter, and d the grill-wire center-to-center spacing. For the displacement Δx at the screen we find

$$\Delta x = \Delta(v_x t) = (\Delta v_x)\frac{2q}{v}\frac{\sec^3\theta}{X+1}\left(\cos^2\theta + \frac{\sin^2\theta\cos^2\phi}{X}\right)$$

$$= \frac{W}{V_a - V_m}\frac{\pi q}{2\ln(\pi D/4d)}\frac{X-1}{1-\sin^2\theta\sin^2\phi}\left(\cos^2\theta + \frac{\sin^2\theta\cos^2\phi}{X}\right) \tag{6.22}$$

Here X is defined by Eq. (6.12). Comparison of Eq. (6.22) and Eq. (6.13)

CHAPTER 7

Beam-Index Tubes

7.1 Principles

Conceptually, the simplest color television system with electron beam scanning is realized by assuming perfect synchronization between the beam exploring the camera tube target overlaid by a three-color filter mosaic and a beam exciting a "white" phosphor overlaid with a geometrically similar color filter mosaic in the receiver. Such a system was proposed by Zworykin (*95*) as early as 1925. Much later Bond *et al.* (*96*) constructed tubes in which proper color reproduction depended on great precision of deflection in one direction (i.e., the vertical) only. The screens of these tubes had horizontal phosphor line triads. Secondary-emitting index markers at the beginning of each line provided correction signals for the vertical deflection which centered the beam on the triad. In addition, a staircase signal at color subcarrier frequency was applied to the vertical deflection to cause the beam to come to rest successively on the red, green, and blue phosphor lines of the triad at the appropriate phase of the color signal. An essentially similar system (without the staircase deflection voltage) was shown to be applicable to a tube with a vertical line screen and precision horizontal deflection.

These systems, too, proved impractical in view of the precision demanded of their deflection systems and the required freedom from disturbing fields. It was soon recognized that in a practical color tube without any masking system, indications of the instantaneous location of the beam relative to the phosphor triad centers would have to be provided over the entire screen area. The problem is solved most readily for a vertical phosphor line screen, on which "beam-index stripes" are provided which are related in some regular manner to the phosphor line triads. The beam-index stripes,

when struck by the scanning beam, must generate a "beam-index signal" indicating the beam location. They may do so, in principle, by acting as beam current collectors, secondary emitters, or emitters of some kind of, preferably, invisible radiation. The preferred types of index stripes incorporated in operating color tubes have been secondary-emitting (magnesium oxide) stripes and UV-emitting phosphor stripes, both deposited on the gun side of the aluminum blanket covering the phosphor screen (Fig. 7.1). The secondary electrons are collected by a positively biased funnel coating of the tube, insulated from the screen. A multiplier phototube mounted behind a window in the funnel coating generates the index signal derived from the emission of the UV-phosphor stripes. A UV filter in front of the multiplier photocathode eliminates ambient light from the radiation otherwise incident on the photocathodes.

In principle, beam-index tubes, like other color viewing tubes, can be either three-beam or single-beam tubes. In three-beam tubes it would be essential that the spots formed by the three beams would precisely maintain their relative separation (in a direction normal to the phosphor lines) with deflection. With large deflection angles this requirement becomes very difficult to fulfill. It is thus not surprising that all operating beam-index tubes described so far have had a single beam modulated by the picture signal.

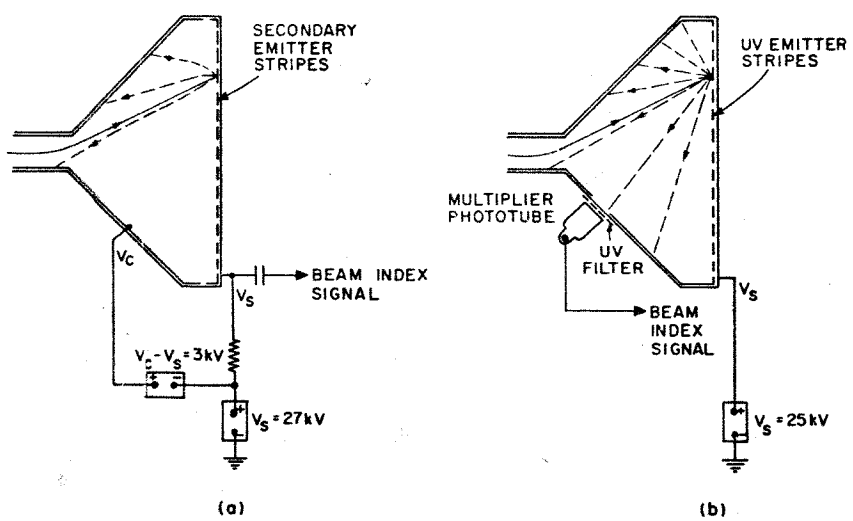

Fig. 7.1. Beam-index signal generation with (a) secondary-emissive and (b) UV-phosphor index stripes.

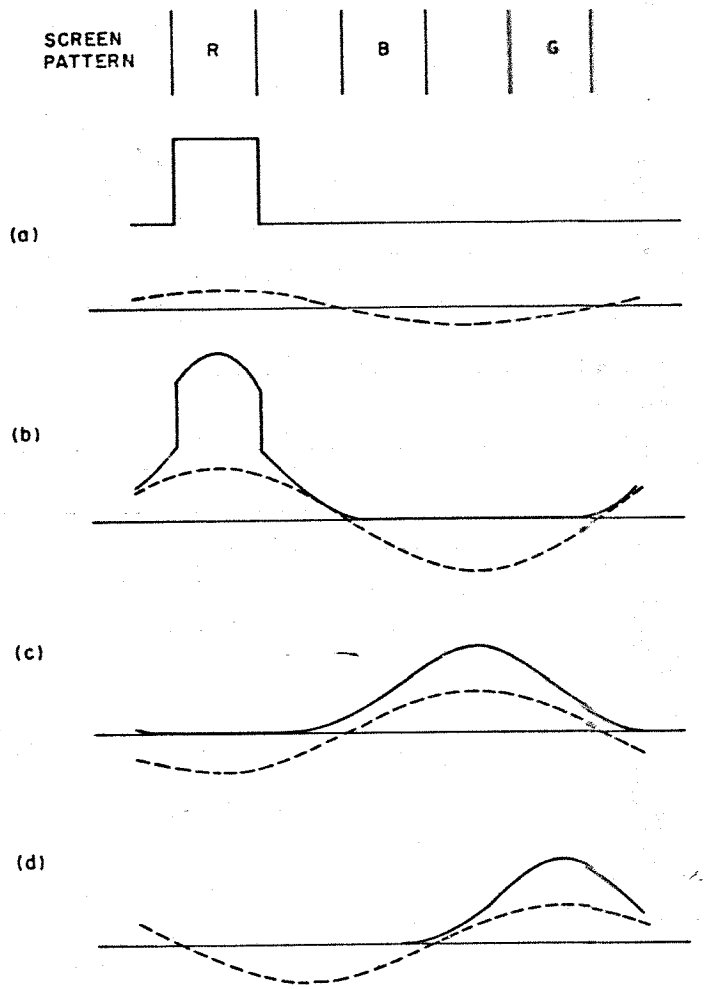

Fig. 7.2. Phase of beam index signal as function of color phase for secondary-emissive index stripe coincident with red phosphor stripe: (a) white field, (b) saturated red field, (c) saturated cyan field, and (d) saturated green field.

The utilization of the index signal also presents alternatives. Thus, a signal proportional to a phase difference between the phase of the transmitted color burst and the simultaneous location of the beam relative to the nearest triad center on the screen may be used as a supplementary horizontal deflection signal, to "correct" the beam location. As an alternative, the same phase difference may be applied to the chrominance signal

applied to the gun grid, so as to bring it in phase with the beam position. The last alternative has been chosen in all the more recently described beam-index systems. It has the advantage of being a simple open-loop system, in which errors need result only from variations in the time taken by the signal to return to the grid, measured in triad periods traversed by the beam. The system which corrects the beam position by supplementary deflection is a closed-loop system, in which, depending on loop gain, the adjustment process may stretch over a number of loop delay times even for uniform horizontal deflection and triad spacing.

The last paragraph assumes that the phase of the beam-index signal is actually uniquely related to the position of the index stripes. This is not generally true. In particular, with the simplest beam-index systems, the phase of the beam-index signal depends on the chrominance signal as well as the index stripe location. Consider, for example, a secondary-emissive beam-index stripe located back of every red phosphor stripe, the screen-current/beam-current ratio of the index stripe being twice that of the aluminum film on which it is deposited, and assume further that the beam-index signal is provided by the fundamental frequency component of the screen current resulting from the presence of indexing stripes. As shown in Fig. 7.2, the phase of the beam-index signal corresponds exactly to the location of the index stripe, in back of the red phosphor stripe, both for a white field (constant beam current) and a saturated red field. On the other hand, for a blue-green field, with the chrominance signal 180° out of phase with the actual index stripe location, the phase of the beam-index signal would be shifted to coincidence with the phase of the chrominance signal. Thus, the beam-index signal could not discriminate between saturated red and its complementary color, and would be totally useless for assuring proper color reproduction.

Various methods have been adopted to minimize the influence of the phase and amplitude of the chrominance signal on the beam-index signal, a phenomenon leading to a hue oscillation commonly designated as "color pulling." In all of them this is accomplished by some form of "frequency separation," i.e., employing a beam-index signal which differs in frequency from the color change frequency. Examples will be described in Section 7.2.

7.2 Index Systems

Two basically different types of beam-index systems have been investigated in detail. One of them, which was the subject of intensive engineering effort by the Philco Corporation in the 1950's and was desig-

which it imposes is tolerable. This is, of course, a property common to all line-screen tubes. It is perhaps of greatest importance in beam-index tubes because of the great cost in terms of picture brightness of any reduction in the color period.

A simple way of reducing the prominence of the line structure with minor adverse effects on other aspects of picture quality consists in placing a molded lenticular filter, with cylindrical lenticules parallel to the phosphor lines, on the faceplate surface (*106*) (Fig. 7.11). The width d of the individual lenticule is made very small compared to the period D_s of the screen structure. If F is the focal length of the individual lenticule in air, h the thickness of the faceplate, and μ its refractive index, the ratio of the width of the lenticule to its focal length is chosen to be

$$d/F = D_s/(h/\mu) \tag{7.14}$$

The modulation transfer function of such a filter for a space frequency (normal to the lenticules) f is

$$\text{MTF} = (f_0/\pi f)\sin(\pi f/f_0), \qquad f_0 = 1/D_s \tag{7.15}$$

Since this vanishes for f_0 and all of its harmonics, the structure becomes invisible and periodic variations of higher space frequency are strongly attenuated. This applies for viewing the screen in a normal direction. When the screen is viewed at an angle, the cutoff frequency occurs at smaller values, corresponding to larger space periods, and the line structure becomes again visible at reduced intensity.

7.4 Summary

Beam-index tubes offer a way of simplifying color tube design at the expense of increased complexity of the auxiliary circuitry. The principal simplifications are the use of a one-piece bulb and the absence of a color-selecting mask or grill. On the other hand, screen preparation is rendered more complex by the addition of an index stripe system. In addition, the currently favored photoelectric system requires a multiplier phototube. While only a single gun is required (again, for the photoelectric beam-index system), the small and sharp spot needed to provide adequate color purity demands great care in the design of the gun and great precision in its fabrication. The potential of the beam-index tube for brightness is comparable to that of the shadow-mask tube, while in color saturation and screen structure it is likely to be somewhat inferior (*98*). Picture sharpness, in the reproduction of both color and monochrome pictures, is necessarily good. Along with other one-gun color tubes, the beam-index tube has the

drawback that it is impossible to adjust the white balance of the finished tube.

Only two types of beam-index tubes, using secondary emission or UV emission to generate the beam-index signal, have been considered in detail in this treatment. Both have demonstrated acceptable performance. It should be stressed, however, that there are many other possible realizations of the beam-index principle, which have been subjected to more or less intensive examination (*106a*).

CHAPTER 8

Penetration Tubes

8.1 Principles

Penetration tubes are color viewing tubes which avoid both the color-selecting mask or grill and the geometrically patterned screen. Instead, the macroscopically uniform screen is made voltage-sensitive, in the sense that the spectral composition of the emitted light changes with the accelerating voltage of the incident beam. This type of screen may be very useful in certain applications, especially where screen structures could present a major problem.

In general, penetration screens have two inherent properties that require special consideration.

(1) The color gamut of the screen and its conversion efficiency are a function of the screen design but inherently cannot equal that obtainable from the basic phosphors used.

(2) The landing position of the beam (or beams) on the screen will change with a color change unless compensation in some form is employed to prevent it. The compensating methods to be employed, as the accelerating voltage is varied to change color, may include high voltage modulation of the screen, deflection sensitivity modulation in analog or digital fashion, and partial beam shielding from the deflection field in multibeam tubes, with use of dynamic correction to obtain register of the color images in much the same manner as for shadow-mask tubes.

8.2 Layer Phosphors

The desired voltage sensitivity of the screens is achieved by arranging the red, green, and blue phosphors in layers, separated in general by layers

of inert or nonluminous materials. Such layered phosphors can be made macroscopically by a uniform layer of one color phosphor on the screen, covered by an inert layer and then a phosphor of a second color, etc. Such phosphor and barrier layers can be deposited in succession as uniform films by evaporation (*107, 108*) or by surface reaction (*109*) onto the faceplate. Techniques have also been developed for depositing on the faceplate phosphor and barrier layers of uniform thickness from suspensions of very fine particles, less than 0.1 μm in diameter (*110*). Alternatively, the very fine particles can be deposited on small core particles, wherein the surface of each small core particle is constituted of three layers having different color properties separated by inert barriers. These three-color surface layers may be formed either on small glass beads or on relatively large core particles of one of the three phosphors (*110, 111*) which act as cores. In either case, the screen emits any of the three primary colors depending on the electron velocity and the penetration depth that ensues.

Both the yellow ZnS(Mn) phosphor films, formed by Studer *et al.* (*109*) by passing Zn vapor over a heated glass substrate in an H_2S atmosphere, and a great variety of phosphor films [$CaWO_4$(W): blue, ZnS(Mn): yellow, Zn_2SiO_4(Mn): green, $MgSiO_3$(Mn) or $Zn_3(PO_4)_2$: red], formed by Feldman (*107*) by evaporation and subsequent heat treatment, exhibited conversion efficiencies of the same order as powder screens. With the evaporated films, heat treatment must be carried to the point of clouding the initially fully transparent films to prevent trapping of radiation within the high-refractive-index medium of the phosphor.

Feldman (*107*) also showed that, with a 0.3-μm layer of $CaWO_4$(W) deposited on top of a 2-μm layer of ZnS(Mn), a shift from substantially saturated blue cathodoluminescence to yellow cathodoluminescence could be obtained by changing the accelerating voltage of the incident beam from 8 to 16 kV. Comparable results were obtained by Koller and Coghill (*108*). More recently, Sylvania has marketed cathode-ray tubes for two-color displays with a screen consisting of a red europium phosphor and a green phosphor separated by a barrier layer, with operating voltages of 6 and 12 kV for the two colors (*112*).

Methods of building up phosphor and barrier layers from suspensions of fine particles have been described by Kell (*110*). In one of these the support surface (e.g., the faceplate) is first coated with a particle-adsorbing substance, such as a 0.1% gelatin solution, and is then thoroughly washed until gelatin is absent from the rinse water, but a thin layer remains on the support surface. A phosphor dispersion (with a concentration of 10–30 mg/cm^3) is then poured on the surface, causing the particles to adhere to the gelatin-coated substrate in a monoparticle layer. The dispersion is poured off and the surface thoroughly washed with water. If this wash is

followed by an acetic acid wash having a pH of 4, the density of the phosphor monolayer may be increased by again applying a phosphor dispersion followed by a wash. The deposition of additional phosphor monolayers may be effected by repeating the sequence of gelatin coating, washing, phosphor deposition, excess phosphor removal, and a final wash. After one phosphor has been laid down to a desired thickness, the same procedure is followed for the remaining barrier layers [using, for example, ludox (silica) or vermiculite (mica) particles] and phosphors.

Precisely the same procedure can be followed in the preparation of multiple-coated particles: The core particles (which may be particles of the phosphor to be excited at the highest operating voltage) are simply coated with gelatin in an aqueous solution, removed from the latter and washed, and then immersed and agitated in a suspension of the fine (barrier-layer

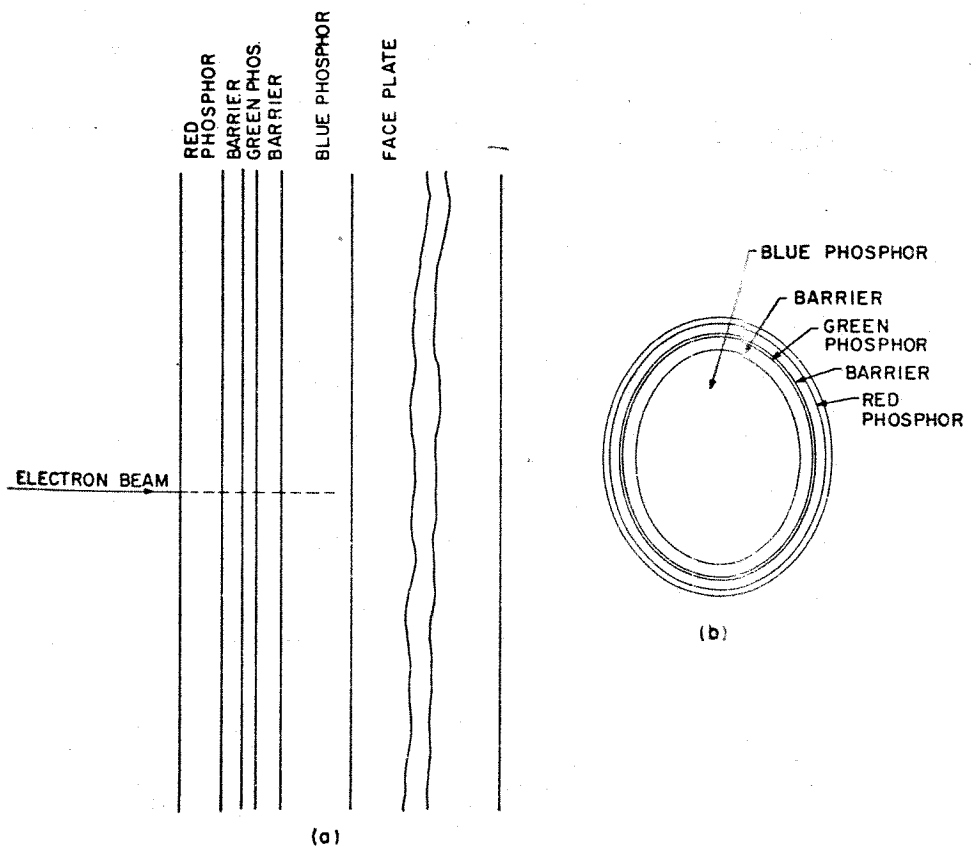

Fig. 8.1. Layered phosphor on (a) a flat substrate and (b) a core particle (schematic).

or phosphor particles to be deposited on the core-particle surface. These processes can be repeated just as for the faceplate layer screen until the complete layer structure has been built up on the core particle. As a final step, a gelatin coating may be applied to the particle and hardened with acid hardener to provide a protective coating.

When the core particles consist of particles of the phosphor to be excited at the highest velocity, Messineo and Thompson (*113*) have produced an integral barrier or nonluminescent layer in the surface of the individual grains by diffusing an emission-killing material into the surface to the desired depth. Prener and Kingsley (*114*) have used homogeneous precipitation of nonluminescent ZnS or CdS to deposit the barrier layer.

The procedure as outlined for multiple-coated phosphors permits the formation of phosphor and barrier layers which are quite uniform in thickness and free from gaps. Unless this condition is satisfied, it is impossible to obtain high-saturation primary colors, since all three phosphors will be excited to some extent even at the lowest operating voltage. Figure 8.1 shows schematically layered phosphor structures on a flat surface and on a core particle. RCA has made available commercially a red-white tube using phosphor of this latter type where the layers are on individual phosphor grains.

The principles which must guide the selection of the layer thicknesses and design methods for multilayer screens for color viewing tubes are described in detail by Pritchard (*111*).

Electrons, in passing through matter, lose energy to the electrons of the medium by inelastic collisions. This energy loss, for electrons in the range of 10–20 kV, with which we are here concerned, is given fairly accurately by the Thomson–Whiddington law (*115*):

$$1 - (V^2/V_0^2) = \rho x/p(V_0) \tag{8.1}$$

Here eV_0 is the initial kinetic energy of the electrons and eV is their kinetic energy after having penetrated to a depth of x cm in the medium of density ρ g/cm³. The mass thickness $p(V_0)$ is the "penetration" of electrons of energy eV_0 into the medium. To a first approximation the penetration, measured in g/cm², is independent of the composition of the medium and a function only of the accelerating voltage V_0. Measurements of Terrill (*116*) on aluminum films led to the relation*

$$p(V_0) = bV_0^n \tag{8.2}$$

* A somewhat better approximation to the range data is given by $p = 4.45 \times 10^{-11}\ V_0^{1.7}$. Also, as W. H. Fonger has pointed out in a private communication, the Gentner curve in Fig. 8.2 necessarily underestimates the energy absorption just below the surface. For a fuller discussion, see Birkhoff (*117*).

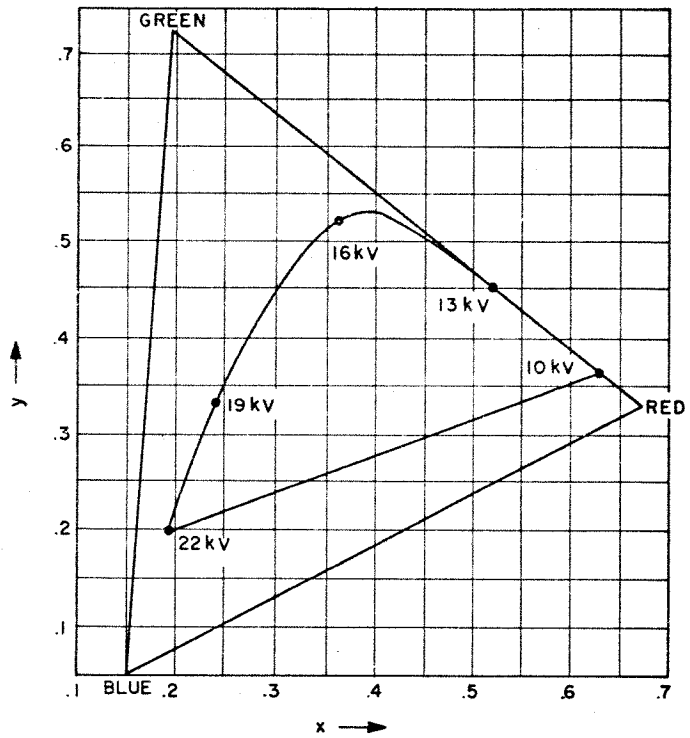

Fig. 8.9. Color gamut for coated particle screen.

8.3 Methods of Operation

As has been noted repeatedly, the layered phosphor screen can be excited either by a single electron beam, generating light of different colors in temporal succession; or it can be excited by three beams, with fixed velocities of impact on the screen, reconstructing the red, green, and blue components of the picture, respectively.

A general block diagram for the operation of the one-gun penetration tube is shown in Fig. 8.10. A fine-mesh electrode maintained at the mean potential V_c of the screen shields the funnel and deflection region of the tube from the varying potential of the screen. A potential difference between the mesh and funnel coating produces an accelerating converging electron lens with focal point at the deflection center which results in approximately perpendicular incidence of the deflected beams on the screen with screen potential (*123, 124*). The screen modulation, at the color sub-

carrier frequency $\omega/(2\pi)$, is synchronized with the color burst so that the proper phase relationship is maintained between the screen potential and the chrominance signal applied to the tube control grid.

The form of the chrominance signal to be applied to the grid depends on the character of the screen modulation. Assume that the screen is modulated by a simple sinusoidal waveform,

$$V = V_0 - V_m \sin(\omega t) \tag{8.20}$$

Then the appropriate signal to be applied to the grid corresponds to a reversing color sequence BGRRGBBGRRGB as described by Loughlin (*103*). If narrow gating pulses are applied at $\omega t = n(\pi/3)$ ($n = 1, 2, 3, 4, 5, 6, \ldots$), the correct color signals E_b', E_g', E_r' are successively applied to the grid for a signal

$$E = \tfrac{1}{3}\{(E_r' + E_g' + E_b') + \sqrt{3}(E_r' - E_b') \sin(\omega t) + (2E_g' - E_r' - E_b') \cos(2\omega t)\} \tag{8.21}$$

The manner in which such a signal may be derived from the transmitted NTSC color signal has been indicated by Loughlin. Without narrow sampling the coefficients of the fundamental and second harmonic terms are slightly modified and the saturation of the reproduced colors is diminished. A waveform which includes fourth-harmonic terms and effects sampling at the appropriate color phases has been given in Eq. (6.26).

It has already been noted that greater constancy of the beam voltage during sampling periods (and, hence, an improved color gamut) is realized by the addition of a second-harmonic term to the screen voltage modulation,

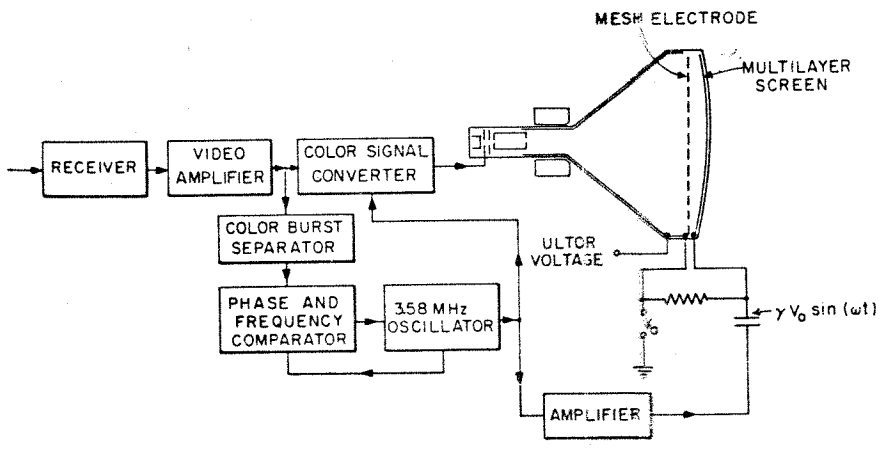

Fig. 8.10. Block diagram for one-gun penetration-tube receiver.

of dc potentials differing by several thousand volts to the cathode. Under the circumstances the dc bias of the individual grids is derived by the rectification of horizontal pulses, capacitively coupled into the grid circuit and rectified there (Fig. 8.13) (*111*).

8.4 Summary

Penetration screens can be formed by the deposition of a sequence of flat layers by evaporation or surface reaction, by the successive laying down of fine-particle screens of different composition, or by the deposition, in a single step, of multiply coated particles on the faceplate. In all cases, the interposition of barrier layers of inactive material between the phosphor layers is essential for the attainment of an acceptable color gamut with a range of beam voltages not exceeding a ratio of 2 : 1. The presence of the barrier layers, as well as the special conditions of preparation of the screen, leads to a reduced overall conversion efficiency of the screen which tends to offset the gain realized by the absence of any form of mask between gun and screen. Furthermore, the color gamut, even when adapted to the special needs of entertainment television by the proper choice of the order of deposition of the phosphors (BGR, from the faceplate toward the gun), is still perceptibly less than for the shadow-mask and other color viewing tubes. One-gun operation requires voltage modulation of the screen which, if done at element rate, would result in circulating powers of the order of tens of kilowatts with attendant radiation-screening problems. With three-beam operation, the gun structure is rendered more complex by the necessity of magnetic screening for two of the guns; in addition, greater demands are placed on magnetic convergence correction than in other tubes.

As of 1973, one-gun penetration tubes are used in limited quantities for commercial applications, but penetration tubes are not used for consumer-type TV displays.

corresponding vertical displacement of the three, red, green, and blue component images relative to each other, by a fraction of a line width, leads to no appreciable deterioration in image definition.

The apparent picture brightness is also proportional to the reduction ratio M. Since, apart from optical absorption and reflection losses, the brightness of the phosphor line image is equal to that of the object, the amount of light intercepted by the eyes of the viewer is simply proportional to the image width, or to M. If T is the optical transmission factor of the system, C, the mean conversion efficiency (measured, for example, in lm/W) of the phosphor screen, I, the average beam current, V, the accelerating voltage, and A, the image area, the image brightness can be written

$$B = (TCIVM)/A \tag{9.1}$$

Here the transmission factor can be held close to 0.9. Spot sizes from 0.5 mm × 0.5 mm at the tube end closest to the gun to 1.0 mm × 0.6 mm at the far end of the phosphor stripes could be realized for $I = 400\ \mu A$ and $V = 25$ kV, yielding satisfactory color purity with a total duty cycle of about 85%. Picture brightnesses up to 100 cd/m² were reported for an image area of 0.12 m². With 16% blanking time, Eq. (9.1) would imply a mean phosphor conversion efficiency of 25 lm/W.

In the Banana tube, the average loading of the phosphor is comparable to that in a projection tube (0.5 W/cm²), although the maximum instantaneous power density is very much less. The metallic substrate with corrugated blackened radiating fins prevents excessive temperature rise and consequent reduction in phosphor efficiency. Sulfide phosphors with persistence less than 0.1 msec are employed to prevent vertical streaking.

Since both the drum and the screen support are blackened, the picture contrast is singularly insensitive to ambient illumination; at any one time, only 1.5 scanning lines of the image area act as effective scatterers of ambient light. However, although the Banana color television system is outstanding in this respect and appears to give acceptable results in picture brightness and definition, the mechanical scanning would seem to constitute a material drawback from the point of view of noise and maintenance. Furthermore, the fact that the picture is at some distance behind the viewing mirror demands, as already noted, that the apparatus be much wider than the picture itself. This would make it scarcely competitive with present compact wide-angle shadow-mask tube receivers.

9.4 Projection Systems

Color television projection systems can operate with three cathode-ray tubes or with a single cathode-ray tube; they may, furthermore, serve

two different functions; the projection of large pictures, suitable for viewing by audiences in theaters or lecture halls, or of pictures suitable for individual viewing, in the home or on color monitors in broadcast studios.

The simplest color projection systems employ three monochrome kinescopes, each mounted in its individual Schmidt projection system, as shown in Fig. 9.6a. The Schmidt projector, consisting of a spherical mirror with an aspheric correction plate near its center of curvature, is universally preferred to projection lenses in view of its very large optical efficiency (F-numbers of the order of 0.7), optical simplicity, and compactness. If the image distance is relatively small, as it is in projection systems for individual viewing, the light from the three Schmidt projectors is superposed by a pair of crossed dichroic mirrors (Fig. 9.5) with the properties that one of them transmits blue and green light and reflects red light, whereas the other transmits red and green light and reflects blue light. The compactness is here maximized and the size of the dichroic mirrors minimized by the employment of folded Schmidt systems (Fig.

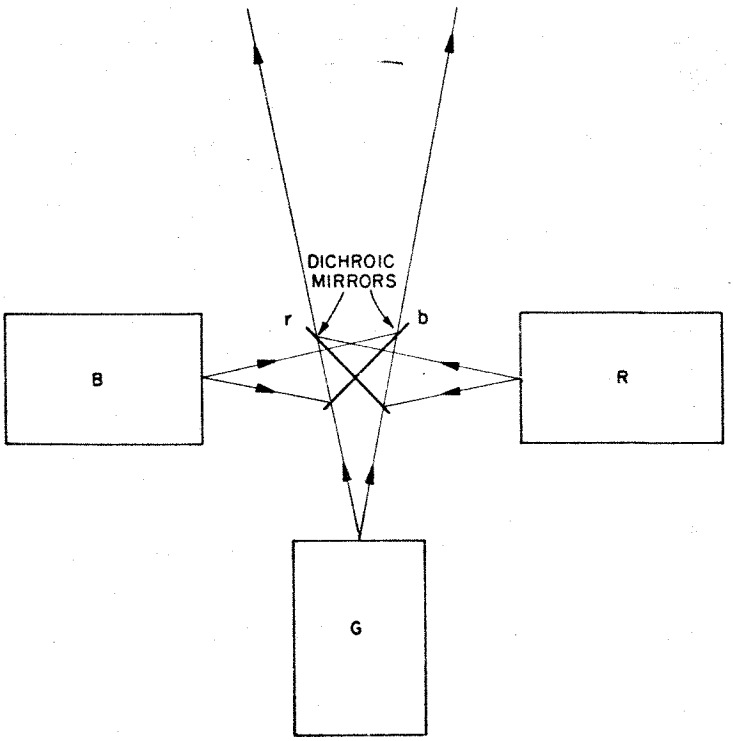

Fig. 9.5. Image superposition with crossed dichroic mirrors.

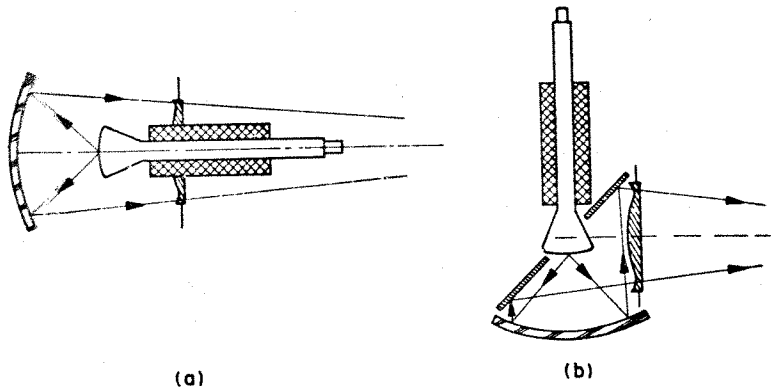

Fig. 9.6. (a) In-line and (b) folded Schmidt projection systems.

9.6b), in which a 45° mirror causes the imaging beam to emerge at right angles to the tube axis. With the dichroic mirrors the optical registration of the three component images is perfect and there are no registration errors, provided that the three optical systems, kinescopes, and scanning patterns are identical.

If the image distance is very large, as is commonly the case in theater projection, the dichroic mirrors become superfluous. The three Schmidt projectors are placed simply side-by-side, the in-line form (Fig. 9.6a) being preferred because of its greater symmetry. The keystone error resulting from the slight tilt of the two lateral systems (Fig. 9.7) required to achieve image superposition can be adequately compensated by a slight modification of the scanning waveforms.

Poorter and de Vrijer (*135*) have studied systems of both types. Pictures 3 m × 2.25 m in size with a maximum luminance of 20 cd/m² were obtained with three 130 mm kinescopes operating at 50 kV in in-line Schmidt projectors; folded Schmidts with crossed dichroics yielded half the screen brightness and lower definition with otherwise similar dimensions. In both cases the directional gain of the screen was 2.8. Smaller pictures (46 cm × 35 cm) with a maximum luminance of 200 cd/m² were obtained with folded Schmidts and dichroics using kinescopes with 60-mm diam screens operating at 25 kV and viewing screens with a directional gain of 7.

Color television pictures of considerably larger size than 3 m × 2.25 m have been projected with Schmidt systems. Thus Evans and Little (*136*) describe a projector with three in-line Schmidts forming images 6 m × 4.5 m in size on an embossed aluminum screen, with a luminance of 18 cd/m². Here the projection kinescopes had 180-mm diam screens and were operated

at 80 kV; the Schmidt mirrors were 660 mm in diameter. Normally, however, Schmidt color television projectors are used only for medium-sized screens (e.g., 1.5- to 3-m diagonal) and employ projection kinescopes of small dimensions (60 mm) and moderate operating voltage (~25 kV) (*137*).

Color television projection systems have also been proposed in which the cathode-ray tubes, instead of supplying the screen illumination, act as light valves, controlling light derived from an external source. The only successful systems of this kind incorporate the Eidophor principle, pioneered by F. Fischer in Zurich (*138*). The Eidophor is also the prototype

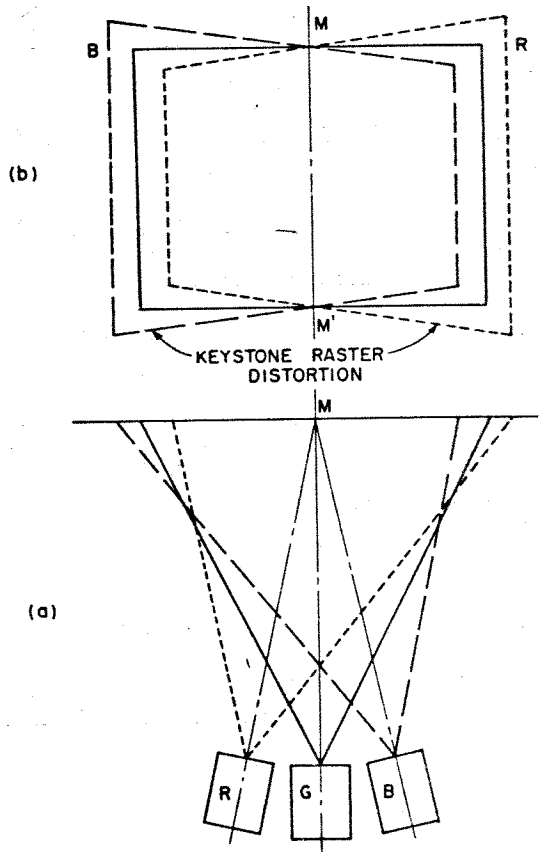

Fig. 9.7. Origin of keystone error in the superposition of images from three projectors placed side by side.

of the ingenious oil-film color projection systems described more recently by W. E. Good (*139*) and his associates at the General Electric Company. In the Eidophor a low-vapor-pressure oil film on the target surface of a cathode-ray tube is inserted in a schlieren optics system which transmits light from a powerful external light source (mercury or xenon arc) to the screen only when high-frequency velocity modulation of the scanning beam imparts a grating-like modulation to the oil surface. For color projection, three Eidophors may be used, the light from the source being first split into its red, green, and blue components by a dichroic mirror system (*140*); the images formed by the three Eidophors are recombined at the screen. Figure 9.8 shows schematically one branch of the system. The incident light is reflected completely by a set of mirror stripes onto the oil film deposited on a concave mirror surface. In the absence of film modulation the light reflected by the concave mirror is fully intercepted by the mirror stripes. With modulation, light is diffracted so as to pass

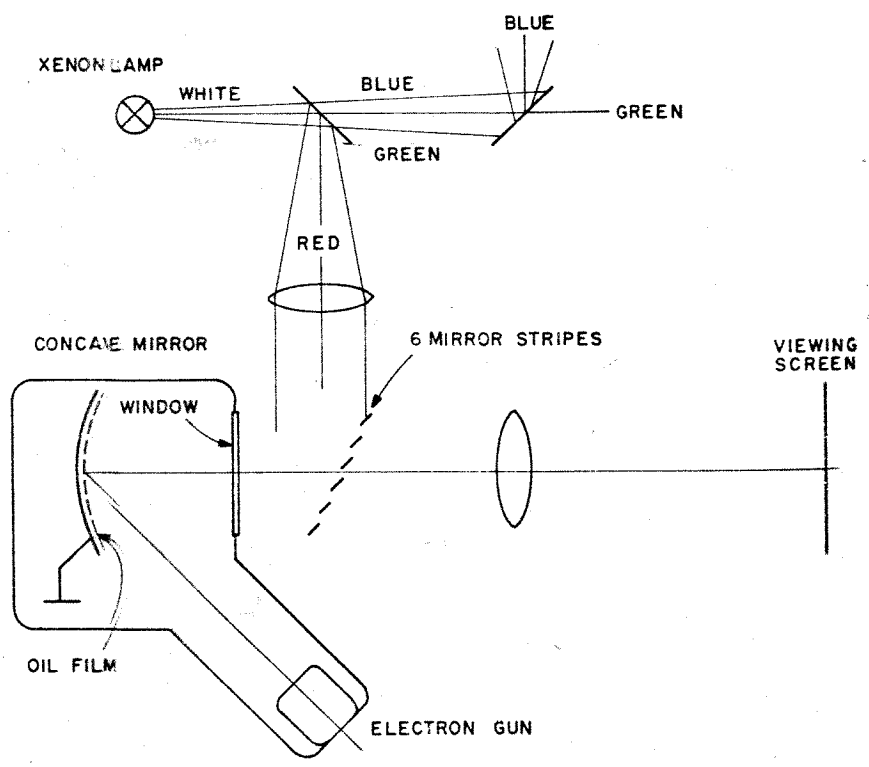

Fig. 9.8. Eidophor system for color projection.

CHAPTER 10

Present Status and Future

Color television picture tubes have been the subject of active research and development since the late 1940's. During this time many reproducer systems have been invented and a few have been intensively investigated in research laboratories. Most, if not all, of the more promising of these have been described earlier in this paper.

Although the shadow-mask system has dominated the field for consumer-type color television displays, there is continuing interest in other systems, mainly because of certain outstanding features the system might have. For example, penetration color kinescopes offer picture reproduction without color-element structure. Beam-index color tubes are characterized by sharp, perfectly registered color pictures since the nature of the tube operation requires a single gun for producing the picture where the gun must deliver a very small electron spot. Focusing tubes are still intriguing because they offer potential large increases in mask transmission with resulting brighter pictures. However, since the early 1960's, most effort has gone into improving shadow-mask tube performance. Many technical details of this work have been discussed in this paper.

Particularly in the United States, great emphasis has been placed on improving picture brightness. Figure 10.1 shows the progress made per unit of beam power through improved phosphors and the use of matrix-screen tubes. Improved electron guns have also contributed to brighter pictures by providing small spots with higher beam current. Operation at voltages up to the limit of practical x-ray protection has been the rule to enhance overall operating performance.

Maximum picture size has remained relatively stable at about 626-mm diag. with a trend to shorter tubes made possible by an increase in deflection angle. Pictures of even larger size and improved performance capability

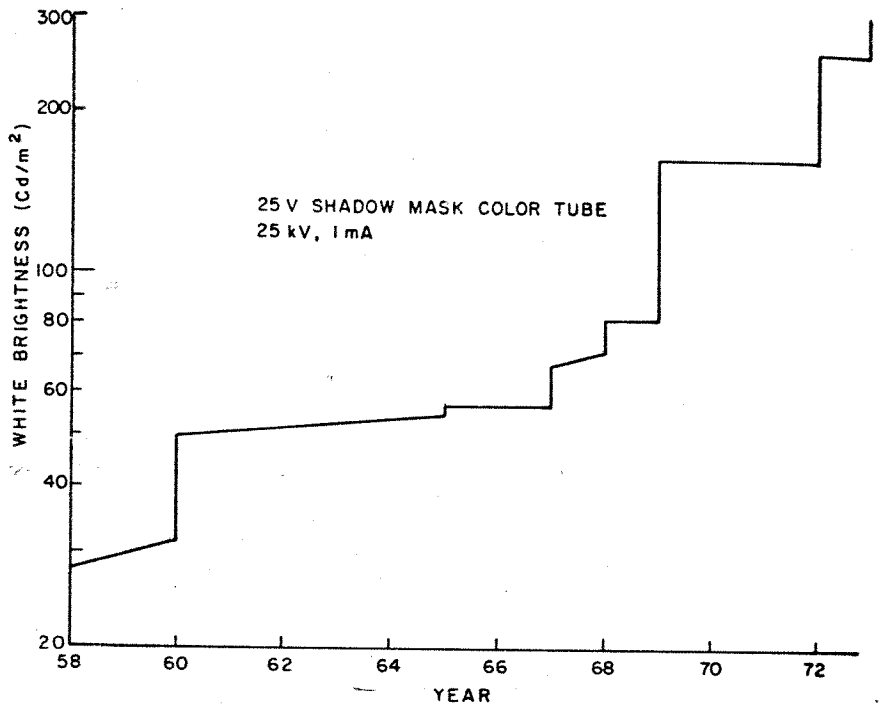

Fig. 10.1. Progress made in improving brightness of shadow-mask color tubes.

may be useful if concepts materialize for an expanded range of services into the home via wideband cable. However, physical and economic limitations are severe for extension of the 626-mm shadow-mask system to significantly larger size. This situation could be avoided if the intensified effort in the early 1970's on thin, flat, commercial matrix displays is successfully extended to displays suitable for color TV picture presentation; but, although great progress has been made through use of solid-state technology, the technical-economic problems yet to be solved for a large, flat, high quality, color TV display are truly enormous.

There is a trend to simplified, small color systems of 480-mm diag. or less, as exemplified by shadow-mask systems employing in-line guns. The in-line geometry has distinct advantages in simplifying convergence or even eliminating dynamic convergence.

Undoubtedly further improvements in color picture tube performance will be made but increasing attention will probably be given to reliability and lowering of costs in order to complement advances made in the receiver system through use of solid-state circuits.

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